UiT The Arctic University of Norway

Faculty of Engineering Science and Technology

Electric snowmobile

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Preface

This master thesis is provided by the Faculty of Engineering Science and Technology at UiT The Arctic University of Norway.

A Polaris Frontier snowmobile with a damaged combustion engine should be modified for battery powered electric drive. An energy system containing battery bank, converters, electric motor and control system should be developed, simulated and tested. The energy system should be installed in the snowmobile, and the performance of the vehicle should be tested. The project could also include display systems for the driver and solutions for regenerative braking, among other things.

This thesis is a practical project making an existing chassis of a snowmobile converted into an operational electric vehicle. Given the physical vehicle and the on-site ordered kit, containing an induction motor, a controller, a "spyglass"-gauge and a menu button. A battery bank, on-board charger, battery management system and auxiliary equipment are suggested by compatibility to the controller and to given configurations of handling/operating electric design.

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Nomenclature

Abbreviations	**Meaning**
EV	Electric Vehicle
BEV	Battery Electric Vehicle
AC	Alternating Current
DC	Direct Current
CVT	Continuously Variable Transmission
BMS	Battery Management System
DIY	Do It Yourself
RPM	Revolutions Per Minute
n_s	Synchronous speed $[RPM]$
f	Frequency $[Hz]$
p	Pole pairs
ω_s	Synchronous angular velocity $[rad/s]$
s	Slip
ω_{slip}	Angular slip velocity $[rad/s]$
ω_m	Angular mechanical velocity $[rad/s]$
J	Inertia $[N\,m^2/s^2]$
T_{em}	Motor torque $[Nm]$
T_l	Load torque $[Nm]$
m	Mass $[kg]$
μ	Friction constant
r	Radius $[m]$
F	Force $[N]$
a	Acceleration $\left[m/s^2\right]$
φ	Incline angle $[deg]$
g	Gravitational acceleration $[9.81\,m/s^2]$
v	Velocity $[m/s]$
d	Diameter [m]
T_s	Sprocket torque $[Nm]$
N	Gear ratio
P_m	Mechanical power $[W]$
n_m	Mechanical speed $[RPM]$
PWM	Pulse Width Modulation
D	Duty Cycle
CCM	Continuous Conducting Mode
T	Period $[s]$
t_{on}	On-time $[s]$
V_o	Output voltage $[V]$
V_i	Input voltage $[V]$
$V_{control}$	Control voltage $[V]$

Abbreviations	**Meaning**
$\hat{V}_{sawtooth}$	Amplitude of a sawtooth signal $[V]$
I	Current $[A]$
L	Inductor $[H]$
R	Resistance $[\Omega]$
V_L	Inductor voltage $[V]$
t_{off}	Off-time $[s]$
Q	Charge $[C]$
C	Capacitor $[F]$
δ	Switch loss constant
Lb Ft	Pound Feet
PM	Permanent Magnet
ECU	Electric Control Unit
CAN	Controller Area Network
FOC	Field-Oriented Control
PMSM	Permanent Magnet Synchronous Motors
MOSFET	Metal-Oxide Semiconductor Field-Effect Transistor
IC	Integrated Circuit
SoC	State Of Charge
SoH	State Of Health
CHAdeMO	CHArge de MOve
VCL	Vehicle Control Language
EEC	European Economic Community

Summary

The main purpose of the project is to convert the snowmobile to electric and make it operational, which rule out focus on factors as ex. driving range, user interface for performance adjustment, heating for comfort, etc.

For mounting the electric motor a suitable and feasible location and motor bracket to easy access the existing gearbox axel, and also in position to a cooling airflow through the hood. The operational design must take into account the RPM at maximum torque for gear ratio and belt speed. Further it is vital to have an on/off switch and a throttle similar to the existing one. This makes the use of a suitable throttle sensor connected to the throttle wire for replacing the carburetor. The direction/neutral switch must be robust, and for easy logical access it will be preferable mounted in the dashboard.

All existing 12 V equipment like headlight, hydraulic braking pump, etc. exclusive the starter and ignition will remain. In addition the converter is also dependent on a 12 V controller supply/circuit, and for mounting of the controller both cooling and shortest possible main wires is crucial for best performance.

The existing instrument panel in the hood will be modified, since the speedometer and the Curtis Spyglass Display are the only two needed and the empty hole of fuel gauge must be covered/closed.

The gas tank will be modified to house the charging socket and charger, for easy physical charging connection access and the position is a central placement between batteries in front and in the saddle. The charger must serve both the power bank batteries and the 12 V battery as a necessity.

Acknowledgements

I will first of all like to thank my supervisor associate professor Trond Østrem, for his support and supervision through this thesis.

I will also like to thank senior engineer Nils Andreassen for making a space available for me in the machine laboratory.

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I also want to thank master student Oleksandr Babych for extra hands when needed and for making a miniature 3D printed model of the chassis parts.

At last I want to direct a thank you to my wife for her patience and support all through my retraining years.

1 Introduction

Conversion of vehicles like snowmobiles, scooters or cars have been and still are considered a niche, though during the last years the market for equipment and materials have expanded greatly, which the increasing number of posted conversion projects on YouTube shows a positive trend of EV conversions.

Converting a former combustion-propelled vehicle to a BEV represents a significant paradigm shift in the automotive industry, driven by the imperative to reduce greenhouse gas emissions, mitigate climate change, and address concerns about air quality and fossil fuel dependence. This master thesis aims to explore the technical and economic aspects of such conversions.

The main purpose of the project is to convert a Polaris Frontier snowmobile from a gasoline combustion engine to an operational electric motor drive energized by a battery pack, and rule out focus on factors as ex. driving range, user interface for performance tuning, heating for comfort, etc. So for making a start, some physical math have to be established by simple assumpted physics to both look into the power required and gear ratio of a added mechanical drive train in chapter 2.3.1. The main components of an electric drive-train are shown in the block scheme and the performance of the purchased kit are presented in figure 1.1.

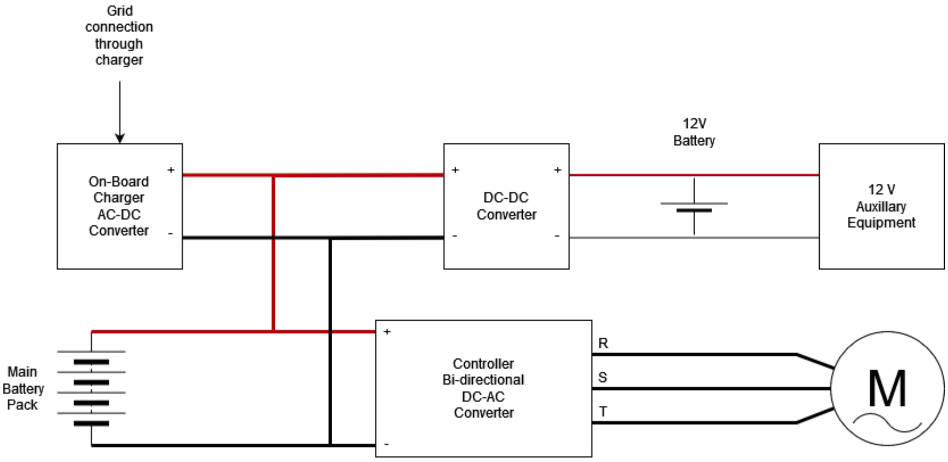


Figure 1.1: Drive-train block scheme. Drawn in draw.io

Before start thinking of the details vehicle for drive-train conversion, the first task is to address the changes made so far and what remains of the original design and equipment. As the thesis say, the combustion engine is being replaced by an electric machine and the energy source of gasoline and tank, are replaced by a battery pack. From Appendix A this replacement will make a natural change in weight distributed on the snowmobile chassis. The Internship Report by Nicolas Pelloux show a suitable placement suggestion in figure 1.2.

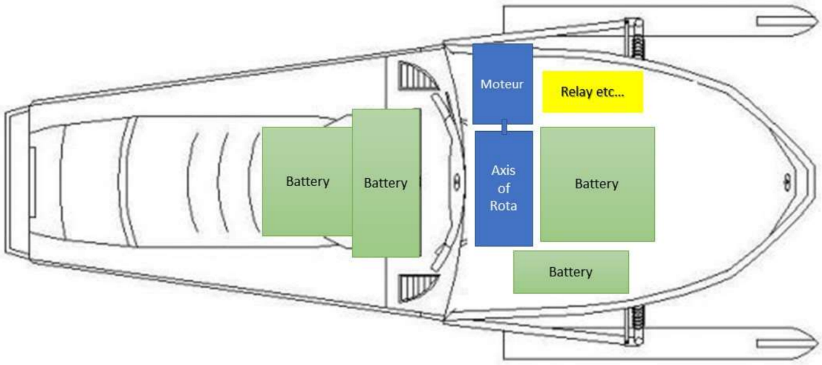


Figure 1.2: shows the suggested placement by Nicolas Pelloux, obtained from page 19 in Appendix A

By replacing the combustion engine the mechanical transmission will also need to be considered, since that originally consists of a “variator”, which is a Pulley-based CVT. This is one of several mechanical issues of the conversion that have to be discussed and evaluated in this thesis.

Further the electrifying of the vehicle will require several parts of equipment to be safe, functional and operational. Since the battery packs are constructed by smaller battery cells of low voltage and capacity into parallel and series for achieving suitable sized battery pack for the purpose of use as energy source. The operation and control is in need of a BMS for maintaining, secure and monitor the state of each series within the assembled pack. This leads to the demand of an on-board charger and a charging safety module to pacify the vehicle when it is connected to the power grid. Further, an inlet socket is needed to make a plugable interface for grid connection through the on-board charger to energize the battery pack.

To reuse some of the original 12 V system, example breaking light, head light, handle and seat heaters, a DC-DC converter will be added to supply the “original” circuits. If this circuit also involves a 12 V battery, it demands a discussion of operation, charging and handling.

To combine circuits of different DC voltage can "easily" be assumed to common ground, which can lead to fatal failure if "floating" ground are present in one of the circuits.

All existing 12 V equipment like headlight, hydraulic braking pump, etc. exclusive the starter and ignition will remain. In addition the DC-DC converter is also dependent on a 12 V controller supply/circuit, and for mounting of the controller both cooling and shortest possible main wires is crucial for best performance.

The existing instrument panel in the hood will be modified, since the speedometer and the Curtis Spyglass Display are the only two instruments needed. The gas tank can be modified to house the charging socket and charger, for easy physical charging connection access and the position is in a central placement between batteries in front and the potential battery placement under the saddle. The charger must serve the power bank batteries and the DC-DC converter to charge the 12 V battery.

For mounting the electric motor, a suitable and feasible location and motor bracket, to easy access the existing variator axle, and also in position to a cooling airflow through the hood for both the controller unit and the motor. The operational design must take into account the RPM at maximum torque for gear ratio and belt speed. Further it is vital to have an on/off switch and a throttle similar to the existing one. This makes the use of a suitable throttle sensor connected to the throttle wire for replacing the carburetor. The direction switch must be robust, and for a logical and not accessible placement it is preferable if mounted in the dashboard.

All the description above include mechanical matters as well as challenges within electrical engineering within the project.

1.1 Literature review

The Internship report of Nicolas Pelloux, depicted in Appendix A, proved the globally stable operation of the induction motor and suggests several feasible solutions, like the already mentioned material placement layout. In preparation for the laboratory test, there was designed and made a temporary circuit card with the least required sensors to operate to operate the controller/motor-kit, which was two $5\,k\Omega$ potentiometers, one for throttle and one braking. Other components was headers for wire connection, a direction switch, a 10 A fuse for the 48 V "High voltage key input" (pin 1) and a switch for the pedal safety interlock (pin 9). The report did not look into the free-rolling-mode, which means to disable the braking-/regeneration-mode, since it was not a considered task of the laboratory test.

1.2 Contributions and scope of the thesis

Electrification of vehicles have become a normalized public opinion, caused by the thought of being environmental friendly. So is it for this project, but the main focus for the author is “clean propulsion” and deliver ideas for a DIY conversion of a combustion engine vehicle. Reuse and minor modifications during such a vehicle conversion, contributes both to reduce cost and time, as well as a minor environmental impact.

The mechanical modifications and conversions can be minor, though essentially to be present before mounting, connecting, testing and tuning the electric drive-train. In addition, the electric equipment and parts have more critical and specific demands for mounting, which must be considered while designing the extended chassis parts.

A vehicle drive-train conversion can be simplified by purchasing a complete kit, which will result to shorten the time in research and chose the matchable and compatible parts. Regarding conversion of a car, a scooter or a snowmobile the design of the electric system is close to equal, though the size in propulsion power and energy in battery package will increase with the size of the vehicle. If purchasing a complete kit there might be an issue of space and weight for the parts, as also in the this snowmobile conversion the space is limited, and as far as possible avoiding to cut in and modify the original chassis and bodywork. Because of this, there was first taken physical measurements and designed a cardboard model of a base plate and the motor bracket, to make sure it would fit in what was the engine compartment under the hood.

1.3 Thesis outline

Through the preliminaries it will be presented a theoretical foundation of physics and the understanding of power electronics and induction motor as implemented components of the conversion. Further through the main results it will be shown suggestions for mechanical, electromechanical, electrical coupling and circuit schemes.

In further work it will be suggested solutions and ideas for the conversion project.

2 Preliminaries

2.1 Formulas

2.1.1 Induction machine related formulas

- Speed of synchronous stator field:

$$n_s = \frac{60 \cdot f}{p} \tag{2.1}$$

- Angular velocity of the synchronous air gap field:

$$\omega_s = \frac{2\pi f}{p} \tag{2.2}$$

- Slip:

$$s = \frac{\omega_{slip}}{\omega_s} = \frac{\omega_s - \omega_m}{\omega_s} \tag{2.3}$$

2.1.2 Physics for the snowmobile climbing a hill at constant speed and ignoring friction

- Moment-of-inertia equation:

$$J\frac{d\omega}{dt} = T_{em} - T_l \; at\, constant\, speed \, \frac{d\omega}{dt} = 0 \Rightarrow T_{em} = T_l \tag{2.4}$$

- Moment-of-inerta of mass onto the driving belt-track gear:

$$J = m\mu r_s^2 \tag{2.5}$$

- Linear forces:

$$\begin{aligned} &\sum F = m \cdot a = 0 \Rightarrow \sum F = F_f - F_r \\ &\Rightarrow F_f = F_r = G \cdot \sin\varphi = m \cdot g \cdot \sin\varphi \end{aligned} \tag{2.6}$$

- Converting linear to angular speed:

$$\begin{aligned} v = \omega_s \cdot r_s \Rightarrow \omega_s &= \frac{v}{r_s} = \frac{v}{\frac{d_s}{2}} = 2 \cdot \frac{v}{d_s} \\ &= 2 \cdot \frac{v}{\frac{Number\, of\, teeth}{\pi} \cdot Pitch} = 2\pi \cdot \frac{v}{Number\, of\, teeth \cdot Pitch} \end{aligned} \tag{2.7}$$

- Torque on belt track driving gear (sprocket):

$$T_s = F_f \cdot r_s \tag{2.8}$$

- Angular speed on motor shaft:

$$\omega_m = \omega_s \cdot \frac{1}{N_1} \cdot \frac{1}{N_2} \tag{2.9}$$

- Torque on motor shaft:

$$T_{em} = T_s \cdot N_1 \cdot N_2 \tag{2.10}$$

- Power out:

$$P_m = T_{em} \cdot \omega_m \tag{2.11}$$

- Motor shaft RPM:

$$n_m = \frac{60}{2\pi} \cdot \omega_m = 9.55 \cdot \omega_m \tag{2.12}$$

2.1.3 Considerations out of torque curve when $n_m = 2500\,RPM$ in flat terrain:

- Torque on track driving gear:

$$T_s = T_{em} \cdot \frac{1}{N_1} \cdot \frac{1}{N_2} \tag{2.13}$$

- Angular speed of motor shaft:

$$\omega_m = \frac{2\pi}{60} \cdot n_m \tag{2.14}$$

- Angular speed of track driving gear:

$$\omega_s = \omega_m \cdot N_1 \cdot N_2 \tag{2.15}$$

- Power out:

$$P_m = T_{em} \cdot \omega_m \tag{2.16}$$

- Converting angular to linear speed:

$$v = \omega_s \cdot r_s \tag{2.17}$$

2.1.4 Buck converter in continuous conducting mode, without losses:

- Duty cycle by PWM:

$$D_{ccm} = \frac{t_{on}}{T} = \frac{V_o}{V_i} = \frac{V_{control}}{\hat{V}_{saw\,tooth}} \tag{2.18}$$

- Lower boundary limit $I_{min} = 0$, for continuous conduction mode inductor size:

$$L_{ccm} = \frac{D \cdot (V_i - V_o) \cdot R}{2 \cdot f \cdot V_o} \tag{2.19}$$

- Inductor voltage when switch is closed (on-state):

$$V_L = V_i - V_o \tag{2.20}$$

- Inductor voltage when switch is open (off-state):

$$V_L = -V_o \tag{2.21}$$

- Rate of change of inductor current in on-state:

$$\begin{aligned} \Delta I_{L_{on}} &= \int_0^{t_{on}} \frac{V_L}{L} dt = \frac{V_i - V_o}{L} \cdot t_{on} \;,\; t_{on} = D_{ccm} \cdot T \\ &= D_{ccm} \cdot (t_{on} + t_{off}) \end{aligned} \tag{2.22}$$

- Rate of change of inductor current in off-state:

$$\Delta I_{L_{off}} = \int_{t_{on}}^{T} \frac{V_L}{L} dt = -\frac{V_o}{L} \cdot t_{off} \;,\; t_{off} = (1 - D_{ccm})T \tag{2.23}$$

- Steady state operated $I_{L,\,t=0} = I_{L,\,t=T}$:

$$\Delta I_{L_{on}} + \Delta I_{L_{off}} = 0 \tag{2.24}$$

- Output voltage ripple:

$$\begin{aligned} \Delta V_o &= \frac{1}{C}\Delta Q = \frac{1}{C}\left(\frac{\frac{T}{2} \cdot \frac{\Delta I_L}{2}}{2}\right) = \frac{T}{8C}\Delta I_L = \frac{T}{8C} \cdot \frac{V_o}{L} \cdot (1 - D)T \\ &= \frac{1}{8} \cdot \frac{T^2(1 - D)}{LC} = \frac{\pi^2}{2}\left(\frac{f_{control}}{f}\right)(1 - D) \end{aligned} \tag{2.25}$$

2.1.5 Buck converter in discontinuous conducting mode:

- Switch loss constant:

$$\delta = \frac{V_i - V_o}{V_o} \cdot D \tag{2.26}$$

- Output current is triangular shaped:

$$\begin{aligned} I_o = \overline{I_L} &= \frac{1}{T}\left(\frac{1}{2}I_{L_{max}}DT + \frac{1}{2}I_{L_{max}}\delta T\right) \\ &= \frac{1}{T}\left(\frac{1}{2}\left(\frac{V_i - V_o}{L}DT\right)DT + \frac{1}{2}\left(\frac{V_i - V_o}{L}DT\right)\delta T\right) \\ &= \frac{\left(V_i - V_o\right)D^2T\left(1 + \frac{V_i - V_o}{V_o}\right)}{2L} \end{aligned} \tag{2.27}$$

Output voltage:

$$V_oD^2T\left(1 + \frac{V_i - V_o}{V_o}\right) = V_iD^2T\left(1 + \frac{V_i - V_o}{V_o}\right) - 2I_oL$$

$$\Downarrow$$

$$V_o = V_i\frac{1}{1 + \frac{2I_oL}{V_iD^2T}} \tag{2.28}$$

2.2 Theoretical preliminaries

2.2.1 Physics

For certainty, some basic physics must be considered to evaluate the power of the purchased motor/controller kit towards handling the snowmobile in flat and inclined terrain, and because of unknown parameters the friction and air drag is ignored. Further, the weight of the vehicle and the driver is set to 325 kg, the added gear ratio is set to $N_2 = 1$ and the first approach considered a constant speed of 60 km/h and incline of 24°. The radius of the driving belt-track gear, commonly known in mechanical term as the sprocket, have only given data as pitch and the number of teeth, shown in figure 2.1, so the radius of the gear is calculated by these and is $r_s = 91,7\,mm$ (2.7).

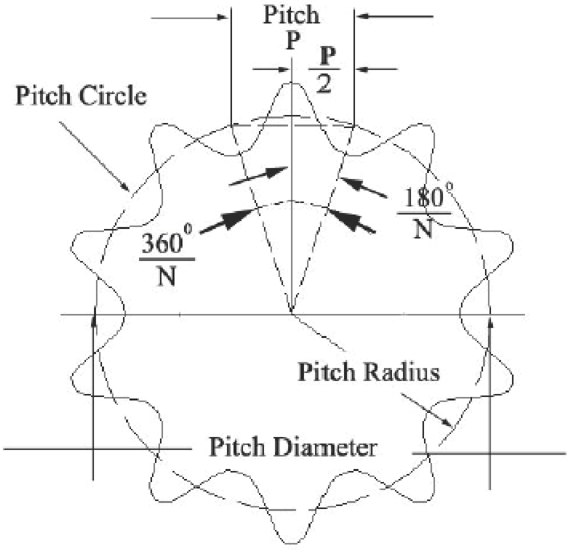


Figure 2.1: Mechanical specifications of the driving belt track gear [2].

First both the linear force on the belt (2.6) and the angular speed of the sprocket (2.7) are calculated by the considered linear speed and climbing incline angle. Through the moment-of-inertia formula (2.4) it is given that a constant speed gives $\frac{d\omega}{dt} = 0$, which turns over to find that the torque (2.10) and power on the motor axle (2.11) with an added 10% system counterforce in form of friction and drag, are 60.6 Nm and 15.9 kW. This shows that the requested power at this incline and speed are within rated value. Since the RPM for the motor, at this vehicle speed, are here higher than the motor speed at the pull-out torque (77.88 Lb Ft = 105.6 Nm), there is also necessary to look into the vehicle speed at this point shown in figure 2.2, which is at 2500 RPM. Using the formulas (2.9), (2.12) and (2.7) the vehicle speed at the pull-out-torque are 40 km/h.

The Moment-of-Inertia on a fixed point at the driving belt-track gear can be determined by a horizontal linear motion of mass with a 10% friction and drag by formula (2.5) giving $J_s = 0.27\,kg\,m^2$. This can be translated to be seen from the motor by multiplying $J_s$with the gear ratio squared $(\frac{19}{41})^2$, which give $J_s' = 0.06\,kg\,m_2$.

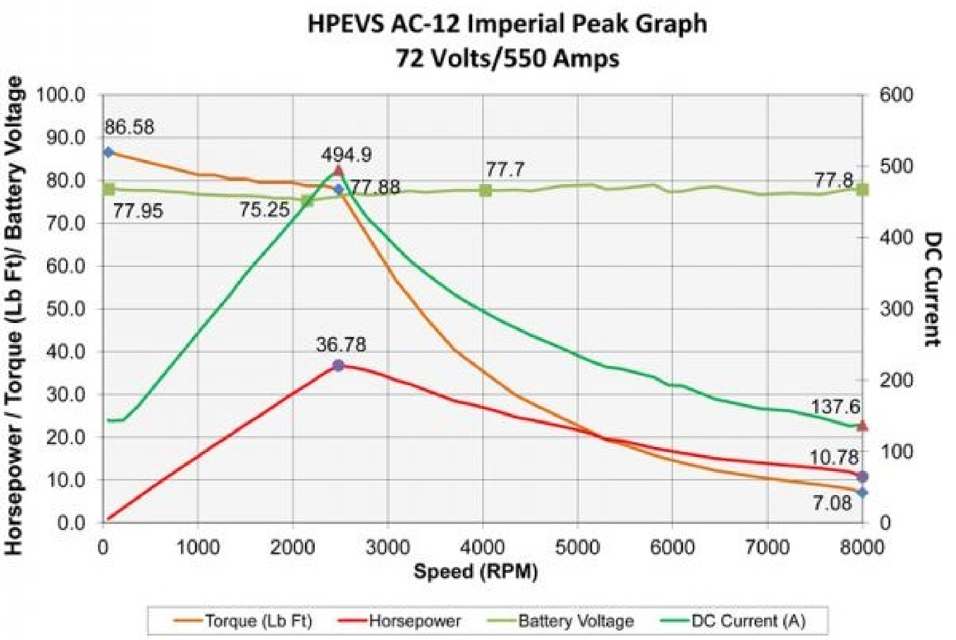


Figure 2.2: Performance graph for the controller of horsepower, torque, output voltage (rated 80 V) and the load current by given speed (RPM) [3].

2.2.2 The induction motor

An induction motor, also known as an asynchronous motor, is a type of AC electric motor that is widely used in various applications, including industrial machines, household appliances, and increasingly in electric vehicles. The motor operates on the principle of electromagnetic induction, where an electric current in the rotor needed to produce torque is obtained by electromagnetic induction from the magnetic field of the stator winding. Induction motors typically consist of two main parts. The stator is the stationary part of the motor and contains coils that are connected to the AC power supply and the coils creates a sinusoidal distributed rotating magnetic field, shown in figure 2.3.

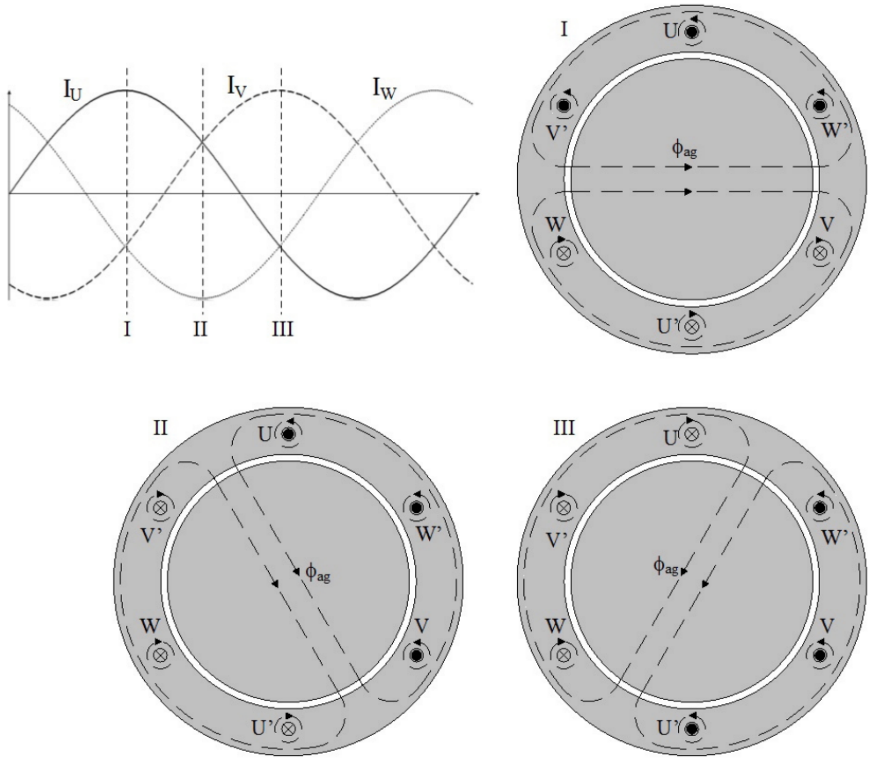
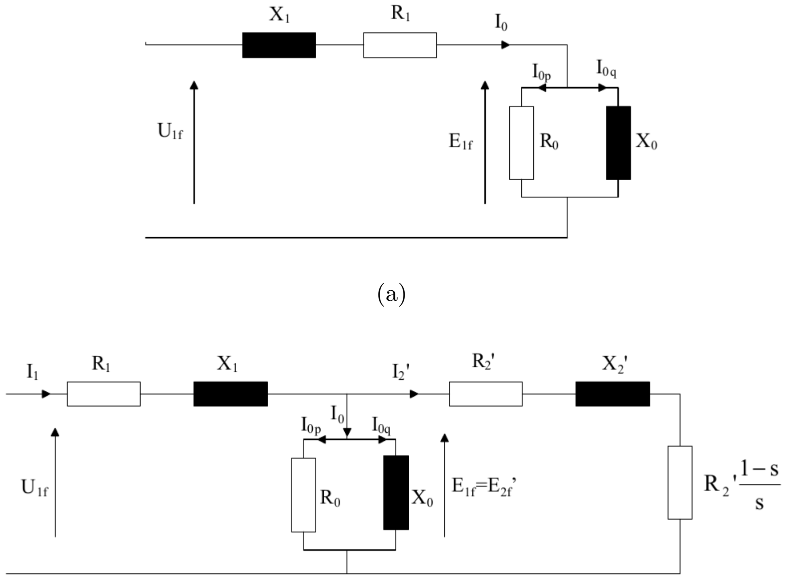


Figure 2.3: The rotating airgap field, obtained from Appendix E.

The rotor is the rotating part inside the stator and is constructed of conductors that are short-circuited by end rings. The rotor can be either wound type or squirrel-cage type, with the latter being more common due to its simplicity and robustness.

To illustrate the electric circuit of resistive and inductive losses, iron losses and induction the use of equivalent schemes, illustrated in figure 2.4, are used to visualize and ease the computing the values of currents, voltages, power out and power losses.



(a)

(b)

Figure 2.4: Phase equivalent schemes for a) no load stator and b) the induction machine, both stator and rotor. Obtained from Appendix E.

The induction of the rotating magnetic field occurs fluctuating current flows through the stator winding, and it generates a rotating magnetic field. The angular speed of this magnetic field rotates with synchronous speed, which depends on the frequency of the AC supply and the number of poles in the motor (2.1). Induction of current in the rotor conductors occurs when the rotating magnetic field passes through the airgap and cuts through the rotor conductors, inducing a current in the rotor due to Faraday's law of electromagnetic induction. The current flowing through the rotor conductors generates its own magnetic field, which interacts with the stator's rotating magnetic field. According to Lenz's law, this interaction produces a torque on the rotor, causing it to rotate in the direction of the stator field.

Induction motors are asynchronous because the rotor always lags behind the stator's magnetic synchronous field slightly. This lagging called slip (2.3), is necessary for torque production. Slip is defined as the difference between the synchronous speed and the actual rotor speed, expressed as a percentage of the synchronous speed. The torque of an induction motor varies with its speed. Typically, there is a high starting torque, reducing as the speed increases until it reaches a maximum pull-out torque at a certain speed and then declines (2.2). Induction motors are generally efficient but can have a low power factor at low loads. Various methods can be used to improve the power factor, such as using passive components as capacitors to reduce the reactive current or active in form of power electronic performing field oriented vector control.

Induction motors are favored for their robustness, low purchase cost, low cost and ease of maintenance. The speed and torque control of an induction motor are more complex than in a DC and PM motors. It has lower starting torque compared to some other electric motor types. Academic studies, car manufacturers and industry applications continue to advance the technology behind induction motors, exploring more efficient designs and control strategies that improve performance across various parameters. The academic knowledge have been established for almost a century, though it is during the last decades made possible through the development in power electronics.

2.2.3 The Controller

In a BEV, the power-train controller is an essential component that oversees the operation of the electric motor and manages the flow of power from the battery pack to the motor shaft. The controller regulates the speed, torque, and direction of the electric motor based on control signals from the built in ECU input from the driver, vehicle sensors, and control algorithms. This ensures smooth and efficient acceleration, deceleration, and regenerative braking, optimizing the utilization of energy stored in the battery pack to maximize driving range and efficiency.

The controller monitors the temperature of the electric motor and other power-train components and may adjust power delivery or activate cooling systems as needed to prevent overheating and ensure optimal operating conditions.

The regenerative braking converts kinetic energy during deceleration and braking into electrical energy to recharge the battery pack. The controller adjusts the level of regenerative braking force based on driving conditions and the driver input to achieve a smooth and predictable braking. The controller communicates with the other vehicle control systems, via CAN Bus protocols, such as the BMS and chassis control modules, to coordinate overall vehicle operation, optimize energy usage, and ensure safety and reliability.

The FOC is a technique used in motor power electronic control systems, particularly in AC induction motors and brushless DC motors, to control the torque and speed of the motor precisely. This technique involves transforming the coordinates of the motor currents and voltages from the stationary reference frame, usually the stator coordinates, to a rotating reference frame, usually aligned with the rotor flux. This makes it easier to control the motor's torque and flux independently, simplifying the control algorithm.

The bi-directional DC-AC converter is here a FOC, using vector control, which is an advanced method of controlling the speed and torque of AC induction motors and PMSMs. This technique allows for precise control of motor operation, mimicking the performance in DC motors, which are traditionally easier to control due to their straightforward relationship between voltage and speed/torque. The fundamental idea behind FOC is to control the stator currents represented as vectors in a manner that they are optimally oriented with respect to the rotor's magnetic field to achieve maximum torque. This involves decomposing the stator currents into two orthogonal components, as the direct component, I_d is aligned with the rotor flux, and mainly influences the magnetizing flux of the motor. The quadrature component, I_q is perpendicular to the rotor flux, and primarily responsible for producing torque, shown in figure 2.5.

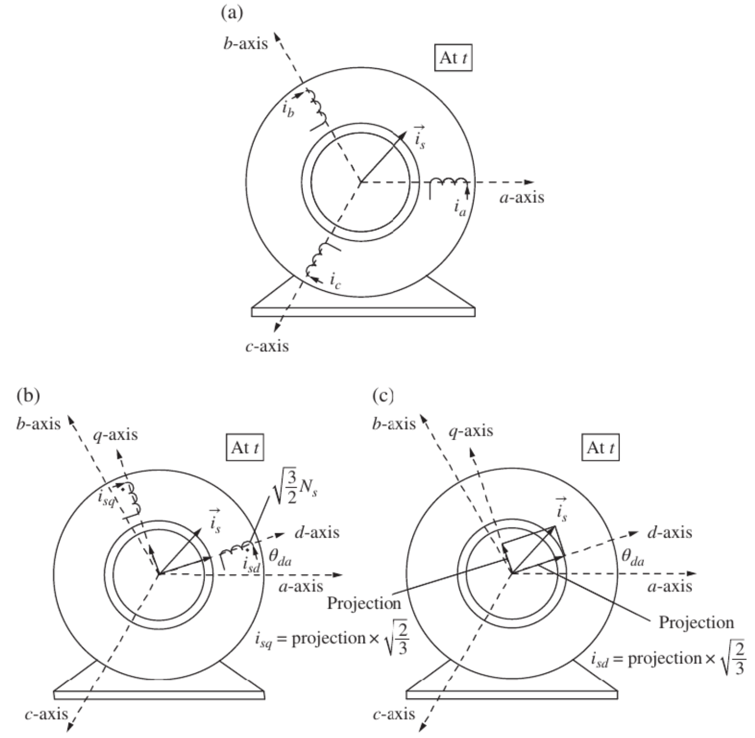


Figure 2.5: [1, p. 342]Static representation of d and q stator windings at time t: a) Stator current space vector $\overrightarrow{i_s}$ is represented by the three phasor currents $\overrightarrow{i_a}$, $\overrightarrow{i_b}$ and $\overrightarrow{i_c}$. b and c)The orthogonal DC components $\overrightarrow{i_{sd}}$ and $\overrightarrow{i_{sq}}$are sinusoidally distributed with the factor “$\sqrt{\frac{2}{3}}$ times the the projections of $\overrightarrow{i_s(t)}$ vector along the d- and q-axis” [1, p. 344].

The Park and Clarke transforms are two key mathematical transformations used in field-oriented vector control. The Clarke transform converts a set of three-phase quantities, such as currents or voltages, from the stationary reference frame, which usually denoted as $a\,b$ and c to a two-dimensional stationary reference α and β frame. This transformation is often used in conjunction with the Park transform. The equations for the Clarke transform are:

$$\alpha = \frac{2}{3}\left(a - \frac{1}{2}b - \frac{1}{2}c\right) \tag{2.29}$$

$$\beta = \frac{1}{\sqrt{3}}\left(b - c\right) \tag{2.30}$$

Where a, b, and c are the three-phase quantities.

The Park transform converts the two-dimensional quantities α and β, obtained from the Clarke transform into a rotating reference frame, usually aligned with the rotor flux of the motor. This transformation simplifies the control of the motor's torque and flux. The equations for the Park transform are:

$$d = \alpha \cos(\theta) + \beta \sin(\theta) \tag{2.31}$$

$$q = -\alpha \sin(\theta) + \beta \cos(\theta) \tag{2.32}$$

Where d and q are the transformed quantities, and θ is the angle of the rotating reference frame with respect to the stationary reference frame.

By using these transforms, the motor control system can operate as if it were controlling a simple DC motor, where the torque and flux are easily controlled independently. This simplifies the control algorithms and improves the performance and efficiency of the motor drive system.

2.2.4 The DC-DC converter

The high voltage to low voltage DC-DC chopper is a crucial component in many electrical systems, particularly in EVs and renewable energy systems. It is designed to convert a high DC voltage input, such as from an EV battery pack, into a typically 12 V DC output, which is suitable for powering low voltage electronics and auxiliary systems. The conversion process in a DC-DC chopper is efficient and can be finely controlled to deliver the required output voltage despite variations in input voltage or load conditions.

A step-down chopper, also known as a Buck converter, is a type of DC-DC converter that reduces the input voltage to a lower output voltage. It's a fundamental component in various electronic systems, including power supplies, battery chargers, and renewable energy systems. The basic principle of the buck chopper operates on the principle of PWM to regulate the output voltage as shown in figure 2.6. The PWM signal can be produced in use of a microcontroller with built-in PWM capabilities or a dedicated timer IC, and if adding an optocoupler or a transformer in between the microcontroller signal circuit and the MOSFET power circuit, galvanic isolation is achieved. The DC input is chopped into pulses using a electronic switch, ex. a transistor or MOSFET, and then filters and regulates these pulses to obtain the desired output voltage.The switch acts as a gate to control the flow of electricity, and it alternates between an "on" conducting state and an "off" non-conducting state based on the PWM signal. The inductor stores energy during the "on" state and releases it during the "off" state. In addition the inductor smooths out ripples by counterforcing changes in voltage and current, providing a relatively stable output. The diode allows current to flow in one direction only, preventing reverse flow when the switch is off, and forms a closed loop with the inductor and load. The capacitor is placed at the output, and filters out voltage ripples, providing a smooth and stable output voltage by the combined setup with the inductor constitutes the function of a low-pass filter.

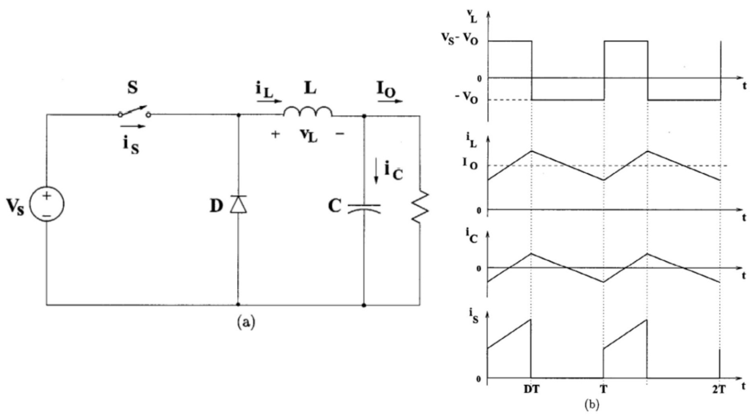


Figure 2.6: a) A basic Chopper circuit, b) the voltage and current curves. Obtained from Appendix E.

The operation during the "on" state with the switch closed, allowing current to flow from the input source through the inductor to the load. The inductor stores energy in the form of a magnetic field, and the output voltage across the load is almost equal to the input voltage. When the switch is opened, the current flow from the source is cut off. So now the inductor releases its stored energy, causing the voltage across it to reverse polarity. The diode allows the inductor current to flow through it, completing the circuit and delivering energy to the load.

By adjusting the duty cycle, which is the ratio of on-time to total cycle time of the PWM signal (2.18), the average output voltage can be controlled. Increasing the duty cycle increases the output voltage, while decreasing it reduces the output voltage. The lower boundary for the duty cycle gives the lowest average output voltage in continuous-conduction mode. If load current are too low the converter will operate in discontinuous-conduction mode, which means the conductor current reaches zero or below, causing the capacitor to start discharge during every cycle and therefore increase the switching losses related to a constant δ (2.26).

The PWM is typically controlled by a feedback loop that adjusts the duty cycle based on the difference between the desired output voltage and the actual measured output voltage through a feedback error control. Buck choppers are highly efficient, especially when stepping down the voltage, and can be designed to be compact and lightweight, making them suitable for various applications. Buck converters also provide regulated output voltage despite variations in input voltage or load conditions.

In summary, the DC-DC buck chopper is a versatile and efficient voltage conversion device commonly used in various electronic systems to step down higher input voltages to lower and regulated output voltages. Its ability to efficiently convert voltages makes it indispensable in modern electronic designs.

2.2.5 The Battery pack

Any vehicle energized by battery can be defined as a BEV, since it is powered entirely by electricity stored in rechargeable batteries and propulted by one or several electric motors. The batteries in BEVs are charged by plugging the vehicle to an electric power source, such as a wall outlet or a charging station.

2.2.6 The Battery Management System

The BMS is essential in managing the operation of a battery pack, typically in applications like electric vehicles, energy storage systems, and portable electronic devices. It ensures the safety, reliability, and longevity of the battery pack by monitoring and controlling its state through various sensors and communication interfaces like the CAN Bus.

The effectiveness of a BMS depends largely on the accuracy and reliability of its voltage, current, temperature, impedance, gas sensors. The voltage is measured both of the entire battery pack and the at each parallel branch of cells. These measurements help in balancing the cells and identifying weak cells that might affect the performance or safety of the battery pack. The current flowing in and out of the battery are measured, and this information is crucial for calculating the SoC and SoH of the battery, and for ensuring that the current stays within safe operating limits. Multiple temperature sensors are used to monitor the temperature of different cells and sections of the battery pack, because of the battery sensitivity to temperature. This data helps in managing the thermal state of the battery to prevent overheating and cold-related performance degradation. Sophisticated BMSs include impedance measurement to assess the health and performance of the battery cells. A BMS can estimate the aging rate of the cells, by measuring the internal resistance.

In cases where battery cells might emit gases due to electrolyte decomposition or other chemical reactions, the gas sensors can detect and trigger safety protocols to prevent hazards and human safety.

2.2.7 CAN Bus

Controller Area Network protocols are crucial in enabling communication between ECUs on-board a vehicle. These protocols, illustrated in figure 2.7, controls the format of the messages, how they are transmitted and processed on the CAN network, by securing that different systems within the network can share information efficiently and function harmoniously using identical protocols.

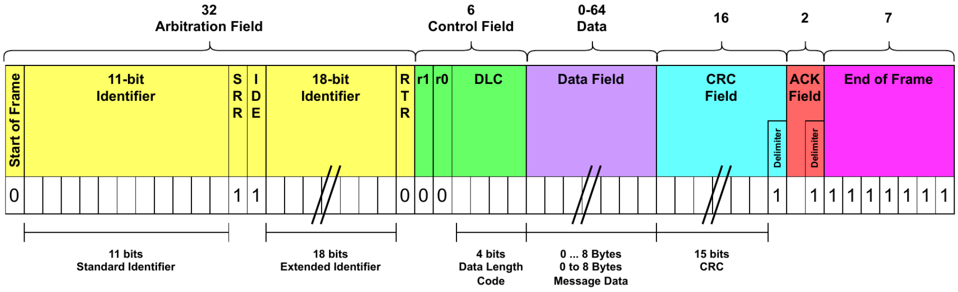


Figure 2.7: Example of a CAN Bus message format. Made in draw.io

Regarding the critical nature of many systems in EVs, the protocols must ensure high reliability and include mechanisms for error handling and fault tolerance. With the increasing connectivity of vehicles, security is a paramount concern, so protocols must include provisions for secure communication to prevent unauthorized access and control of vehicle systems. EV architectures may vary widely, from small personal vehicles to large commercial buses. Protocols must be scalable and flexible enough to accommodate different sizes and complexities of the vehicle systems.

In an EV, the CAN Bus protocols facilitate efficient and timely sharing of critical information across systems. The battery charge levels and health data being sent from the BMS to the vehicle's central unit. Drive control commands sent from the vehicle's central unit to the motor controller, and the regenerative braking data are sent from the drive systems back to the BMS and vehicle controller.

The choice of protocol can depend on the vehicle manufacturer's preferences, the specific functions required by the vehicle systems, and the overall design philosophy of the vehicle's electronic network. As EV technology continues to evolve, the protocols will also adapt to support more advanced features and functionalities.

2.2.8 The on-board charger

In a BEV, the onboard charger is the component with the primary function of converting AC power from the external source into DC power suitable for charging the vehicle's battery pack. Typically, this involves a rectifier and voltage output regulation, though bi-directional power converters have been introduced for making the BEVs to be contributing elements in a Smart Grid. The onboard charger determines the maximum power and charging rate at which the vehicle's battery pack can be charged by communicating with the BMS. The charging power is measured in kW, and the charging rate affects the time it takes to fully charge the battery. The onboard charger are designed to operate with specific charging connectors and protocols, such as Type 1 (J1772) or Type 2 (Mennekes) connectors for AC charging, and Combined Charging System or CHAdeMO for fast high voltage DC charging.

Further, the onboard charger must be designed with safety features to protect against overcharging, overload, overheating, short circuit, and other potential hazards as example grounding faults. These safety features contains fuses and system monitored sensors, which contributes to ensure the safety of the user, the vehicle and the charging equipment.

Most of the onboard chargers include communication interfaces, such as CAN bus to communicate with the vehicle's BMS, power-train controller and other systems. This allows for coordination between the charger and the vehicle's power management system.

Overall, the onboard charger is a critical component of a BEV's charging system, allowing the vehicle to be conveniently charged from external power sources and ensuring efficient and safe operation. As battery technology and charging infrastructure continue to evolve, the onboard chargers evolving to support faster charging rates, improved efficiency and bi-directional power flow.

3 Main result

3.1 Equipment and Electromechanical designs

The purchased motor and controller kit defines the overall electric drive train with control and sensor configurations. Through this chapter it will be presented a selected solution of compatible equipment, control circuits and components, mechanical as well as electromechanical solutions.

3.1.1 Reusable

The mechanical speedometer need no modification at all, since it is directly coupled to the axle for the belt track gear and not influenced by modifications of the preceding gears, gearbox and engine solution.

The present 12 V DC wire harness consists of both reusable auxiliary components as headlights, taillights, brake light, handlebar and saddle heaters, and not usable wire harness with interfaces/connectors related to the removed combustion engine. All the auxiliary circuits are directly operated by a switch and not by a relay design. Further, the ignition key is not present, which can be locally purchased at ex. Biltema or Thansen, though the wires and relay for this are present in the harness, the specific wires must be equipped with suitable connectors for the purchased ignition key.

The present braking system is a conventional hydraulic system with a braking disk and caliper coupled to the former variator axle. The brake handle is placed on the left side of the steer, equipped with a small brake fluid reservoir and an endswitch to activate the brake light.

3.1.2 The brake system

A brake fluid pressure transducer is requested for the controller to activate regenerating/braking mode and brake light signal on pin 3 on the 35-pin controller interface, which transform the system from a pure mechanical into a electromechanical system. To simplify the physical implementation the transducer can be mounted directly in between the caliper and brake fluid pipe, because it only requires a Y-coupling and matching threads which makes the modification easy and quick. A transducer and the caliper with hydraulic pipe is shown in figure 3.1.

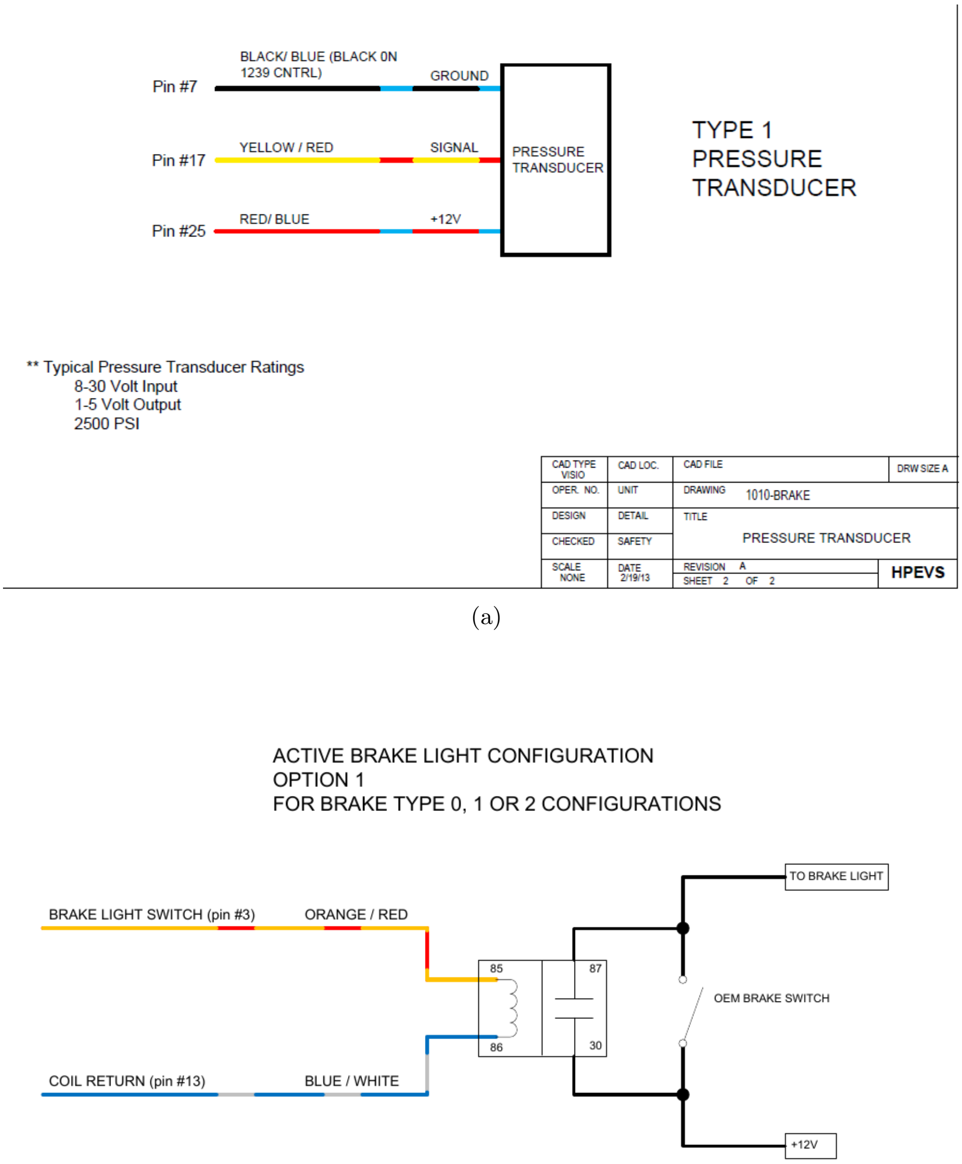
(a)

(b)

(c)

Figure 3.1: a) The present state of brake caliper. b) Brake pressure transducer [4]. c) Y-coupling [5].

Figure 3.2 shows the pressure transducer input as brake type 1 configuration, and the active brake light output configuration option 1 referred to the 35-pin controller interface.



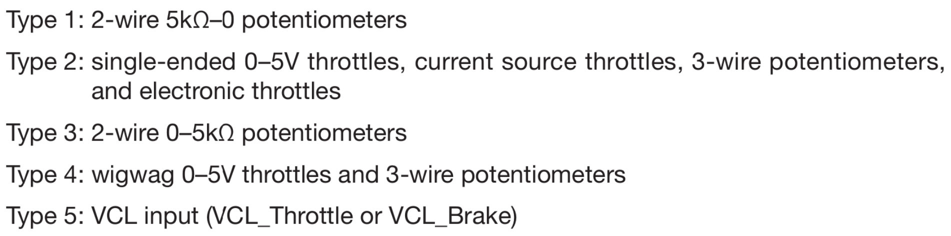
(a)

(b)

Figure 3.2: a) Controllers pin connection for the pressure transducer. b) Brake light activation circuit. Both figures obtained from Appendix F.

3.1.3 The throttle system

The controller have five types programmable throttle setups, shown in figure 3.3.



Type 1: 2-wire 5kΩ–0 potentiometers

Type 2: single-ended 0–5V throttles, current source throttles, 3-wire potentiometers, and electronic throttles

Type 3: 2-wire 0–5kΩ potentiometers

Type 4: wigwag 0–5V throttles and 3-wire potentiometers

Type 5: VCL input (VCL_Throttle or VCL_Brake)

Figure 3.3: Types of programmable throttle configurations. Obtained from page 20 in Appendix D.

Because a 3-wire $0 - 5\,k\Omega$ potentiometer have already been used in laboratory test and because of the present throttle wire, the EV West Billet Aluminum Throttle Potentiometer**,** depicted in Appendix C, with the 3-pin single output are selected because in use of this “the controller provides full fault protection in accordance with EEC requirements” [Appendix D, page 25]. With the 3-pin connection the potentiometer operates as a voltage divider with a source circuit and return circuit. The source circuit is wired from the potentiometer Pot High to pin 15 and Wiper to pin 16. The return circuit is wired from pin 18 to Pot Low, through the wiper to pin 16.

To automate the potentiometer return to a rest position, the most common technique is in use of a spring hooked to the throttle arm, shown in figure 3.4. Even though the potentiometer throttle have both an internal spring and a shaft mounted torsion spring, there is required an external spring for safe operation to push or pull the throttle arm back into the rest position.

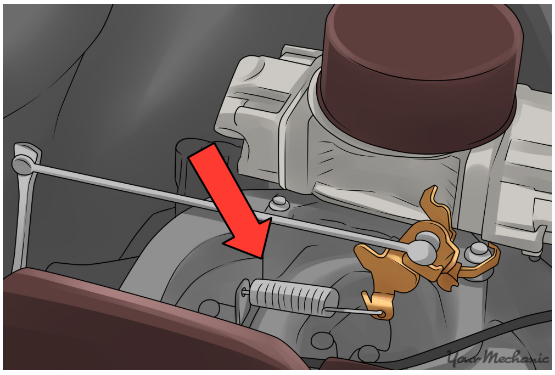


Figure 3.4: A throttle arm with a pulling return spring [6].

One of the main issues was to solve a solution for the free rolling mode, which is solvable as confirmed and described in the Appendix D, page 13 regarding Switch 6/pin 12 and the presence of a normally closed endswitch at the throttle handle, which will be connected to pin 12 and 25. “On when regen braking is taking place; Off when it is not.” [Appendix D, page 74]. With the throttle active, the endswitch will be closed, set pin 12 high and actuate the regen braking mode. When throttle is at rest, pin 12 will be set low, and the free rolling mode is activated.

The interlock function to disable such as the throttle are suggested performed by connecting pin 6 on safety device AVC2 to pin 9 on the controller interface. Pin 6 on the safety device are a normally closed switch, which will open when battery charging is taking place or when the key switch is turned off.

3.1.4 Charging safety

Safety is a paramount concern when it comes to charging BEVs. Standardization contributes to that the charging infrastructure, such as charging stations and home charging setups, complies with safety standards and regulations. Only equipment used are certified and properly maintained to minimize the risk of electrical faults or failures. Charging cables and connectors require the user to inspection for any signs of damage or wear before use. Damaged cables or connectors must not be used, as they can pose a safety hazard. The cables used are rated for the appropriate charging power and compatible with the vehicle’s charging inlet.

All charging equipment must be properly grounded and installed according to manufacturer instructions and technical standards. All charging equipment have built-in overload protection to prevent excessive current flow, which can damage the vehicle’s electrical system or cause a fire. Circuit breakers and fuses must be installed as part of the charging circuits/system to protect against overload events and grounding fault, as well as the temperature of the charging equipment and the battery pack during charging are monitored to prevent overheating. Charging in extreme temperatures is a challenge, as it can reduce charging efficiency and potentially damage the battery. Today BEVs come equipped with safety features to protect against overcharging, over-discharging, and other charging-related hazards. The user must familiarize with these features and follow manufacturer instructions for safe charging practices. User education and training on proper charging procedures and safety precautions, on how to use charging equipment safely and how to recognize and respond to potential hazards can help mitigate risks associated with BEV charging. By following the safety guidelines and taking appropriate precautions, BEV owners and operators can ensure that charging their vehicles is a safe and reliable process. Regular maintenance and inspection of charging equipment, along with adherence to safety best practices, are essential for minimizing the risk of charging-related incidents.

3.2 Electrical circuits

The modified 12 V harness consists of circuits for key-ignition, head and tail lights, brake light, horn, handlebar and saddle heaters shown in figure 3.5. The main circuit schematics can be seen in Appendix B.

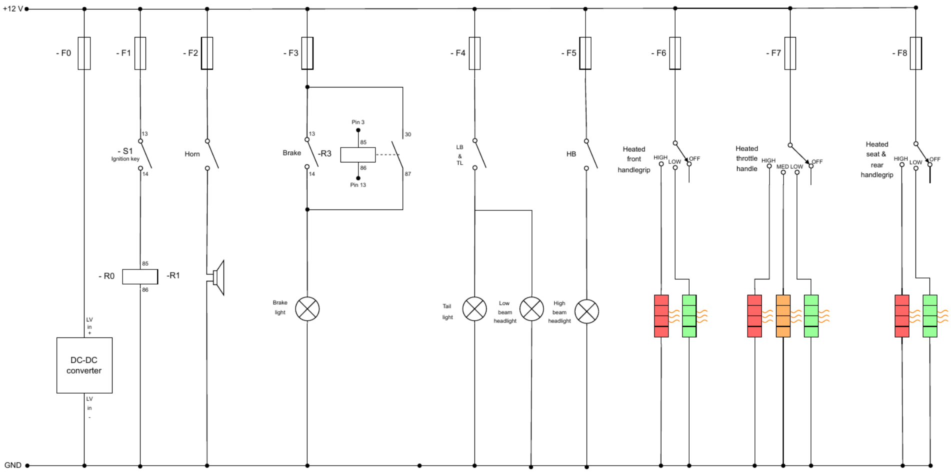


Figure 3.5: The electrical 12 V auxiliary circuit for the snowmobile. Made in draw.io

3.3 Mechanical drive train

The variator transmission is suggested replaced by a chain and two gears, which gear ratio is set to 1, and sized to reduce the need of a chain tension gear, seen in figure 3.6.

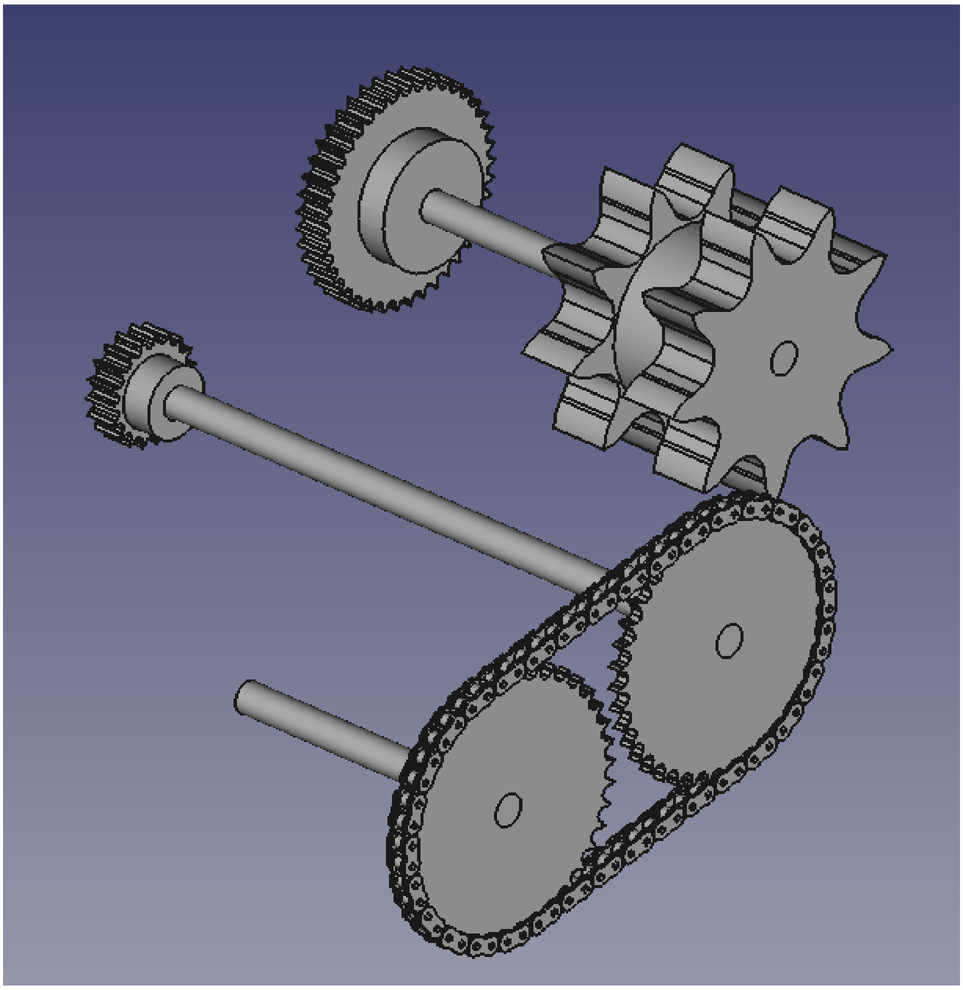


Figure 3.6: Suggested transmission from motor axle to variator axle. Designed in FreeCad.

3.4 The motor bracket

A solid chassis for motor assembly and a required flat surface to mount the Curtis controller, was first cut and modeled in cardboard to size it to fit onto the base plate and into the available space under the front hood, illustrated in figure 3.7.

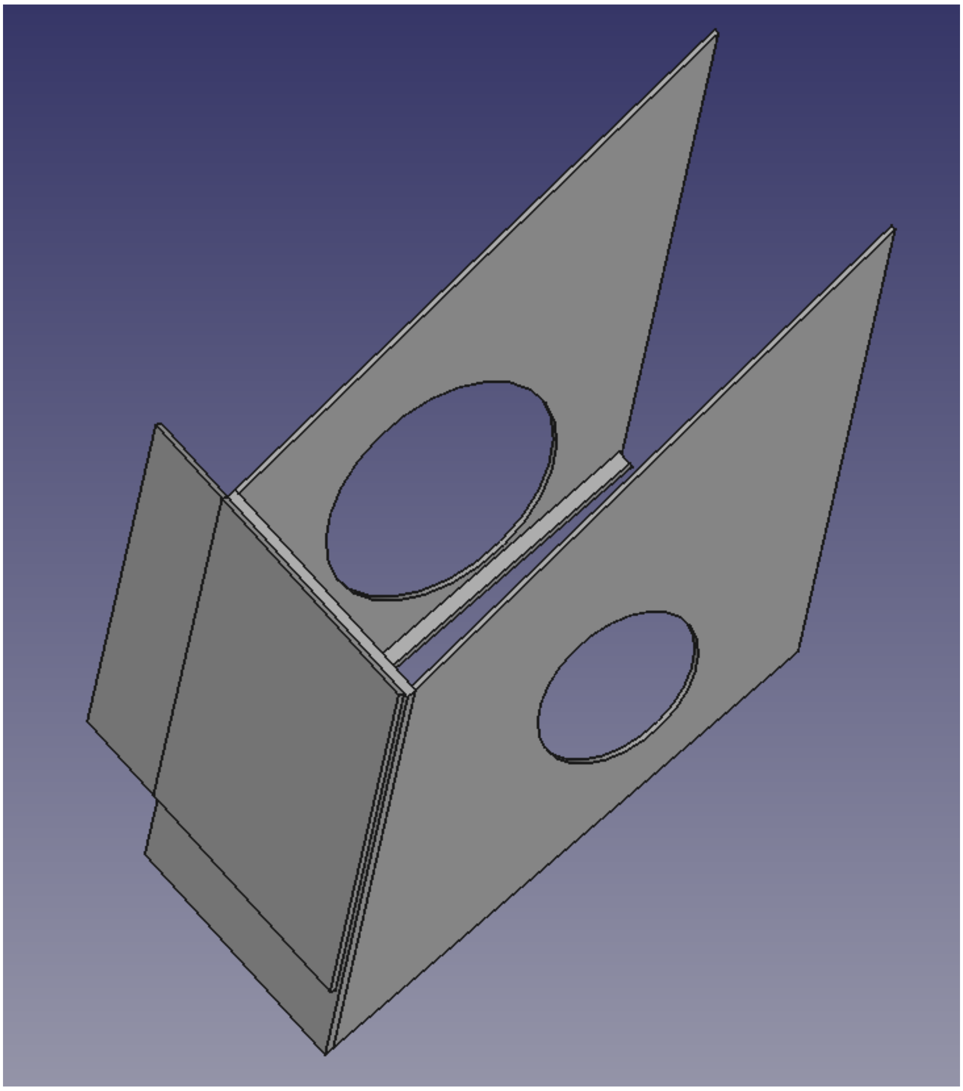


Figure 3.7: Design of the bracket for mounting the motor. Designed in FreeCad.

3.5 The base plate, the motor bracket and the mechanical transmission

To illustrate the suggested additional chassis design and mechanical transmission, all designed parts were assembled as shown in figure 3.8.

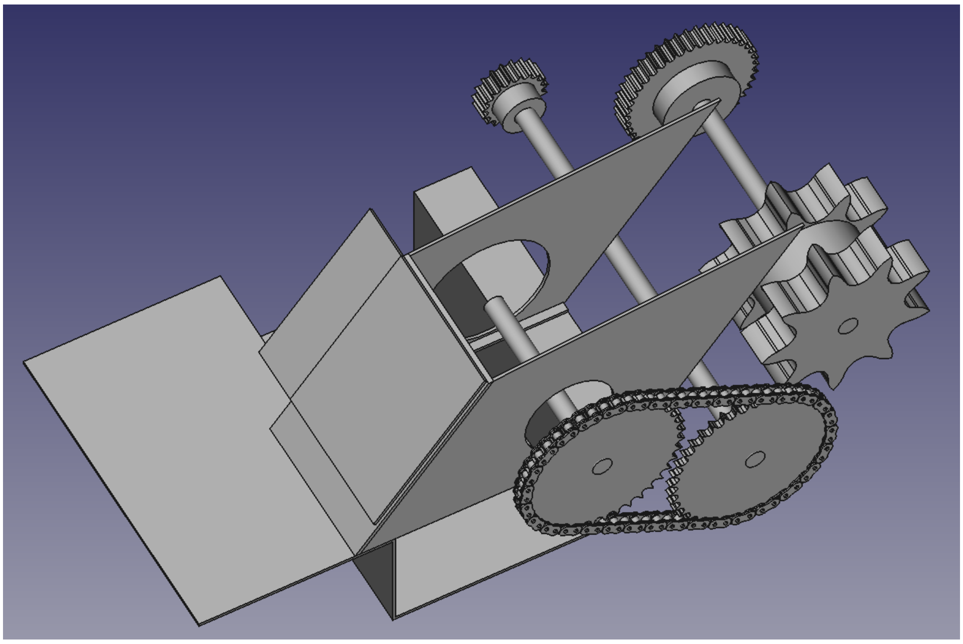


Figure 3.8: All parts assembled. Designed in FreeCad.

3.6 Part list/order list

A list of suggested project equipment and parts is depicted in Appendix G.

4 Discussion

The project did not deliver an operational electric snowmobile, so the considerations here have to regard the suggested theoretical solutions for the mechanical and electrical proposals.

Battery and BMS are either integrated in the battery-packs or separate, though common for such systems are CAN Bus communication with the controller and/or on-board charger. The controller are pre-programmed to be set up with among others, the compatible Orion BMS, which in turn referring to a number of battery brand, current sensors and chargers for compatibility. With internal BMS the programming of the CAN Bus is a necessity for communication with the controller and/or the on-board charger. Because of the increased complexity and amount of hours of programming and testing the CAN Bus communication between the BMS, controller and on-board charger the given lists of compatible components are preferred for reasons like time effort and technical brand support of chosen equipment.

5 Conclusion

The report can be concluded to have suggested solutions and design strategies that address the core issues identified in the main results. These solutions include both immediate and long-term approaches. By implementing these recommendations:

- Delivering a satisfying mechanical design for chassis extension and transmission.
- A satisfying solution for enabling the free rolling mode are accomplinglesly described in subsection 3.1.3.
- The presence of the endswitches at the throttle and the brake handle saves both money and time when not needed to be purchased, designed and mounted.

The project aims to achieve significant improvements in performance and sustainability, ensuring that the objectives are met effectively and future challenges are mitigated.

5.1 Future work

The extended chassis part of a base plate and motor/controller bracket are suggested to be manufactured at a local metal work shop like Namek or Bamek, since the tools for bending the required plate thickness is not present at UiT campus. If it is made on campus, each side can be cut individually and welded, but this set critical quality requirements to the strength of the welding work.

Every suggested component that communicates by CAN Bus are preprogrammed and compatible, which reason is to simplify the conversion. Though it could be considered to ignore compatibility, for a real programming challenge in form of a thesis.

The present mechanical gearbox is equipped with a forward/reverse gear mechanism, which are both unused and excessable. The whole gear box could be removed and replaced by the proposed motor gear and chain transmission.

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A Electric Snowmobile Report by Nicolas Pelloux

POLYTECH Clermont

Internship Report

Conversion of a combustion snowmobile to an electric snowmobile

04-04-2022 to 24-07-2022

- **School** : UIT Norges Artic university of Narvik
- **Internship supervisor** : ØSTREM Trond
- **School supervisor** : LENGAGNE Sébastien

PELLOUX Nicolas

Years 2021-2022

Abstract

During my fourth year of engineering school at POLYTECH Clermont, I did an internship abroad from April 04th to July 24th, 2022, at Narvik University under the supervision of Mr TROND Østrem.

The aim of this report is to study the conversion of a thermal snowmobile into an electric snowmobile. This project fits perfectly in the current world because it brings an ecological vision in a field which tries today to reduce its carbon footprint. Moreover, with the increasing fuel costs in the world, this desire to convert thermal vehicles into electrical vehicles is more interesting. Also, snowmobile travel is common in this part of the world (about 7 months of the year are covered by snow).

Throughout this report, many points will be discussed specially to detail the progress of the project such as the security which remains particularly important in view of the voltages and currents that are managed. We will also approach a part of wiring the motor and the controller which will lead us to the creation of a card which will facilitate the wiring of the controller. We will then have a precise programming procedure to follow. This part will logically lead us to the first tests of maximum speed, speed management, braking ... Afterwards, we will analyze the results of the different tests to have an idea of the consumption, of how the engine reacts by modifying the speed and the torque. Finally, we will suggest a positioning of the material within the snowmobile (the one that will surely be used in the future).

Keywords : snowmobile, electric, conversion, motor, controller

Résumé

Dans le cadre de ma quatrième année d'école d'ingénieur à POLYTECH Clermont, j'ai effectué un stage à l'étranger du 04 avril au 24 juillet 2022 au sein de l'université de Narvik sous la tutelle de Monsieur TROND Østrem.

Ce rapport a pour but d'étudier la conversion d'une motoneige thermique en une motoneige électrique. Ce projet rentre parfaitement dans le monde actuel car il apporterait une vision écologique dans un domaine qui cherche aujourd'hui à réduire son empreinte carbone. De plus, avec la hausse des carburants dans le monde, cette envie d'aménager les véhicules en véhicules électrique est d'autant plus intéressante. Aussi, le loisir et le déplacement en motoneige est courant dans cette région du monde (Environ 7 mois de l'année enneigé).

Au cours de ce rapport, de nombreux points seront évoqués pour détailler le cheminement du projet comme la sécurité qui reste très importante au vu des tensions et courants qu'on manipule. On abordera aussi une partie câblage du moteur et du contrôleur qui aboutira à la création d'une carte facilitant grandement le câblage du contrôleur. Cette partie, nous emmènera logiquement vers des premiers tests de vitesse max, de gestion de vitesse, de freinage etc… On aura ensuite une procédure de programmation précise à suivre. Puis viendra l'analyse de résultats des différents tests afin d'avoir une idée de la consommation, de comment réagit le moteur en modifiant la vitesse ainsi que le couple. Enfin on proposera un placement du matériel au sein de la motoneige (celle qui dans le futur sera surement utilisée).

Mots clés : *motoneige, électrique, conversion, moteur, contrôleur*

REMERCIEMENTS

First of all, I would like to thank **Mr TROND Ostrem**, my tutor at the UIT Norges Artic university in Narvik, for the internship proposal, the hospitality within the university, his supervision, and his help all along the project. He also gave me the opportunity to explore this part of the world by advising me.

I would also like to thank **Mr. LENGAGNE Sébastien**, my internship advisor at POLYTECH Clermont, for his help during the different steps of the procedures and his support along the whole internship.

I would like to thank **Mr. Alexander PANKRATOV** as well as the team of engineers and technicians of Narvik university for their help, their trust, and their support throughout this internship period.

Finally, I would like to thank my family and friends who have been a real help to me through regular contact.

Table of contents

TABLE DES ILLUSTRATIONS

List of acronyms and abbreviations

PCB	Printed Circuit Board
RPM	Revolution per minute
DC	Direct Current
BMS	Battery Management System
Pm	Mechanical Power
Pelec	Electrical Power

Glossary

Battery Management System	It is an electronic system allowing the control and the charge of the various elements of a battery.
Breadboard	It is an experimentation board which allows to realize a prototype of an electronic circuit.
Controller	Hardware device that could be programming to manage or directs the flow of data between two entities.
Deathband	It allows us to have an idea of the precision in our case of potentiometers
Main contactor	It is an electrically controlled switch used for switching an electrical power circuit.
Plexiglass	solid and transparent plastic material which is used as protection in our case.
Potentiometer	Variable resistor used to adjust (in our case speed and braking).
Printed Circuit Board (PCB)	It is a plate that has the purpose to maintain and connect as desired components in order to realize a complex electronic circuit.
Relay	A relay is an electrical device that distributes power based on an order issued by the control unit.
Test Bench	it is an environment used to test and control our hardware. In our case the engine, controller ...
Torque	The only effect of a couple is to produce or prevent the turning of a body.

* All words with an asterisk are defined in the glossary.

I. Introduction

The fourth-year internship, which lasts four months and is an integral part of the program offered by POLYTECH Clermont, it gave me the opportunity to do an internship abroad and more specifically to integrate the UIT Norges Artic university in Narvik.

The Narvik University, Norway, gave me the opportunity to work in a laboratory with advanced technological equipment in a rapidly growing field. I had the opportunity to acquire solid technical and organizational skills for my entry into the workforce.
During this period, I was able to immerse myself in a new culture but also in a new vision in technical terms as well as in terms of safety during handling.

Today, and even more tomorrow, electric vehicles are becoming more and more important in our society because of their ecological and economic vision (increase in gas prices). Therefore, the project of converting a thermal snowmobile into an electric one is completely in line with the times. Questions can quickly appear such as "How can we do it? What equipment is needed?"

Indeed, this project is even more interesting in this part of the world where the displacement by snowmobile is common, but also necessary with the mountains in the surroundings (Approximately 7 months of the year covered with snow).

To answer the various problems, we will initially refix certain important information via research, which was made, without forgetting to make a first point on safety which was a very present point during the internship. The wiring part will allow us to identify and understand the functioning of our equipment. Following that, the starting of the motor and the controller* will bring us several tests and thus by the same occasion the analyses of this one. Finally, solutions will be proposed for the placement of the equipment within the snowmobile.

II. The project : Snowmobile

A. Pre-project research

To get a better idea of the project, we had to do some research on the first equipments available. In our case, a motor, a controller*, a display, a relay* and a button (See fig 1). To carry out the wiring of the motor, controller as well as the battery, a good choice of cable is then necessary. With the different graphs below and research (see fig 2), we get important information such as the maximum value of voltage, current, torque* etc... (48V-80V and 550A). After having recovered this information, we just have to choose the section of cables adapted for our connection, in our case the section will be 90mm2.

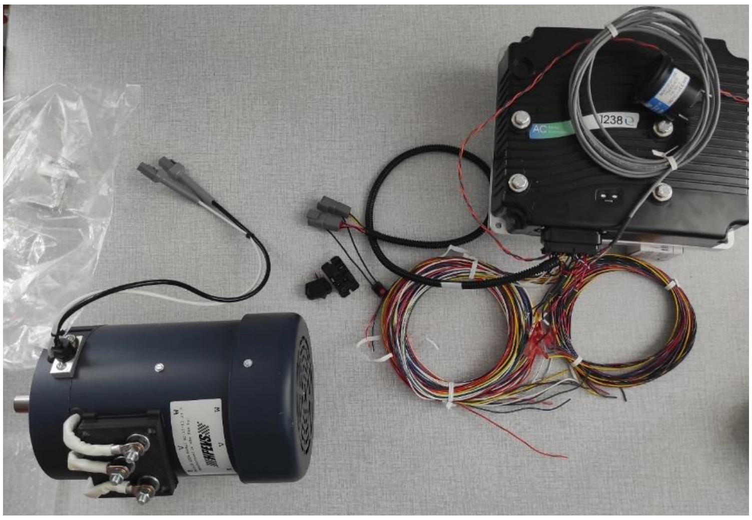


Figure 1: equipements

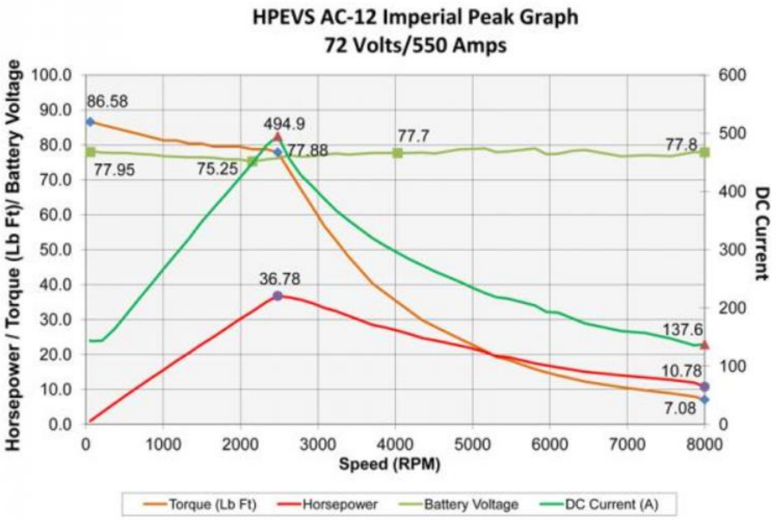


Figure 2: Peak graph

Now we must look at the documents that talk about the wiring in order to prepare a list of components that would be necessary. In this list we will find, a key switch which will be replaced by a switch to facilitate the tests, a main contactor* (LEV200A6NAA 5-1618388-8, See fig 3), two potentiometers* (0-5kΩ), two switches, a fuse (12V-20A). However, for the test parts, the main contactor* will be replaced by a solution proposed by the engineering team because the command of it would have taken too much time. We will discuss in the next parts the wiring diagrams.

Figure 3: Main contactor

B. System security

We enter in a part which was present throughout the project, for this first point on the safety we are going to speak about protections which we had to set up to reduce the risks during manipulations. On this part, the objective is to protect the connections (see fig 4), because during the operation, we will work with huge values of voltage and current, there are then risks which could cause physical damage.

Small safety point on the cables : it is necessary to understand that a section of electric cable too small and which is strongly solicited can cause a heating of the core of your cable (which can be in copper, aluminum or other metals) because there is too much intensity, this is because there is too much current, therefore too many amperes flowing through the cable and because of this overload of current, the electrical conductors will heat up and melt the plastic insulation that protects them, and in the worst case, cause a fire.

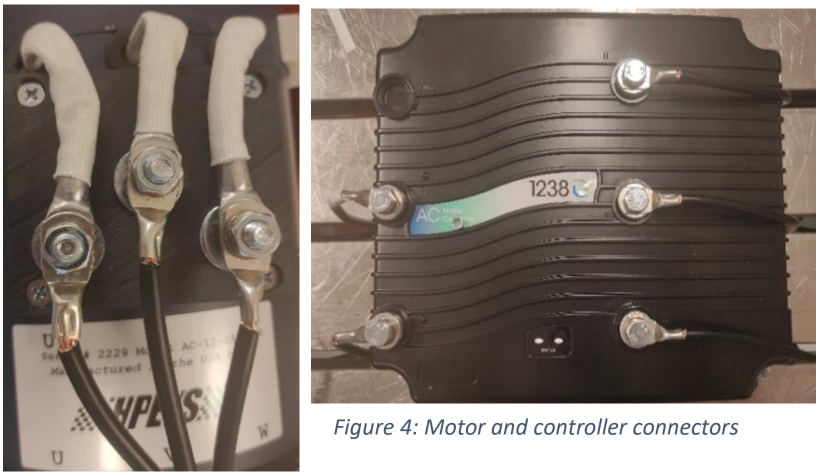


Figure 4: Motor and controller connectors

To manage this problem, we had to recover different measures, but also propose a protection in paper model (See fig 5).

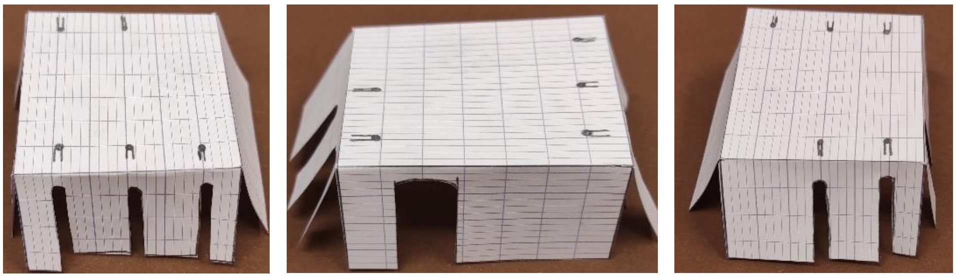


Figure 5: Protection prototype

Finally, the protections have been made in plexiglass* and in real size (see fig 6). The protections below, will greatly reduce the risk of mishandling because no connector is reachable without removing the covers.

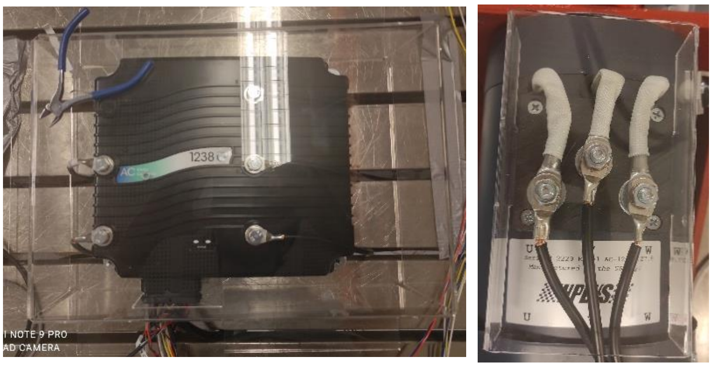


Figure 6: Full size protection

III. General cabling

A. Cabling

In this part, the comprehension of some documents is necessary (see appendix 1 and 2 for the wiring diagrams), indeed, these documents offer us the total wiring of the controller but also the way in which we must wire our potentiometers (see fig 7).

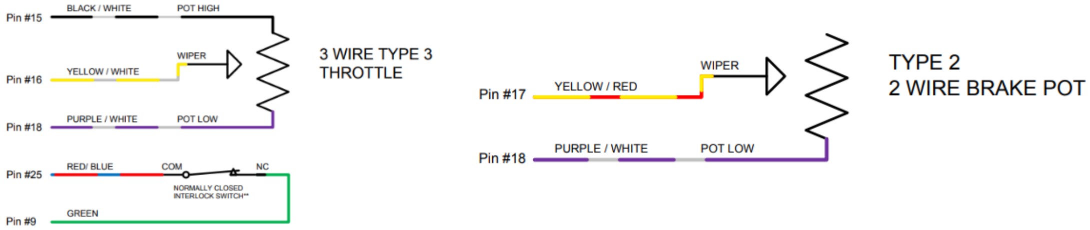


Figure 7: type of potentiometers

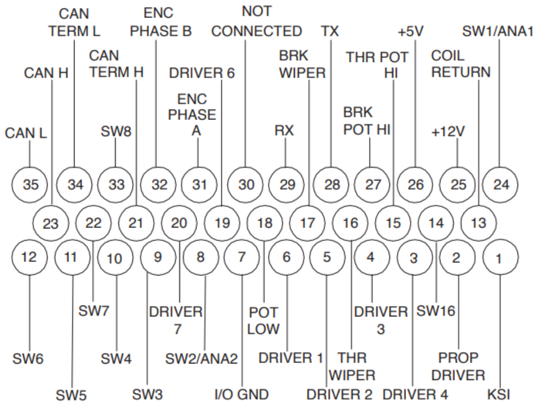


Figure 8: Connector Wiring

For a clearer view of the project, a small diagram of the connector will help us to identify which cables are useful for a good wiring of the controller (See fig 8).

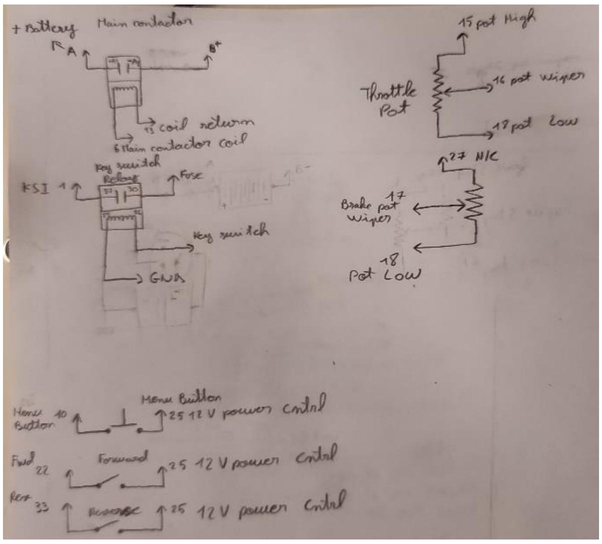


Figure 9: Schematic

Now, the objective is to propose reduced schematics, which, in the future, will allow us to develop a card facilitating the cabling and decabling that we will see in the next part (see fig 9).

Here is now a picture of the finished wiring (See fig 10). We notice that the solution of the engineers to replace the main contactor was to add resistors to lower the voltage in order to activate the relay* and then the contactor.

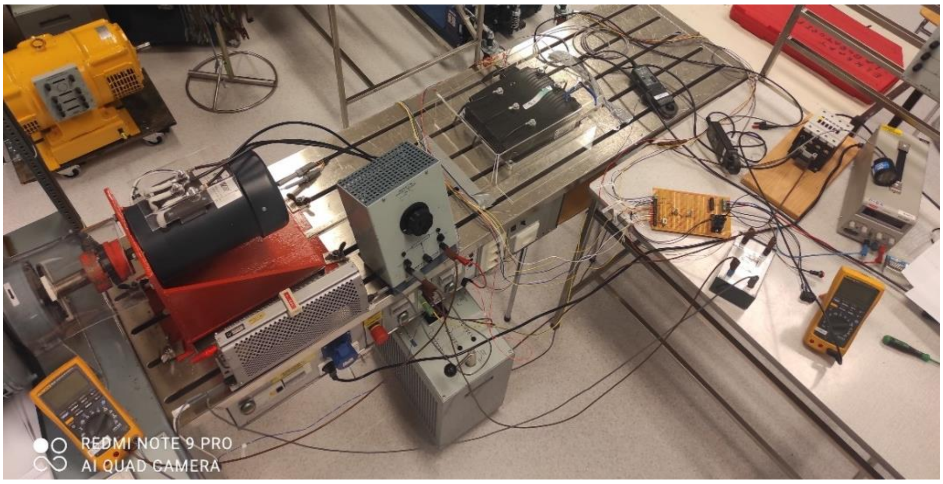


Figure 10: General wiring

Finally, to close this part, we put on each cable of the controller a label (See fig 11) with the number of the cable and its meaning (for example +12V) corresponding to the diagram figure 8.

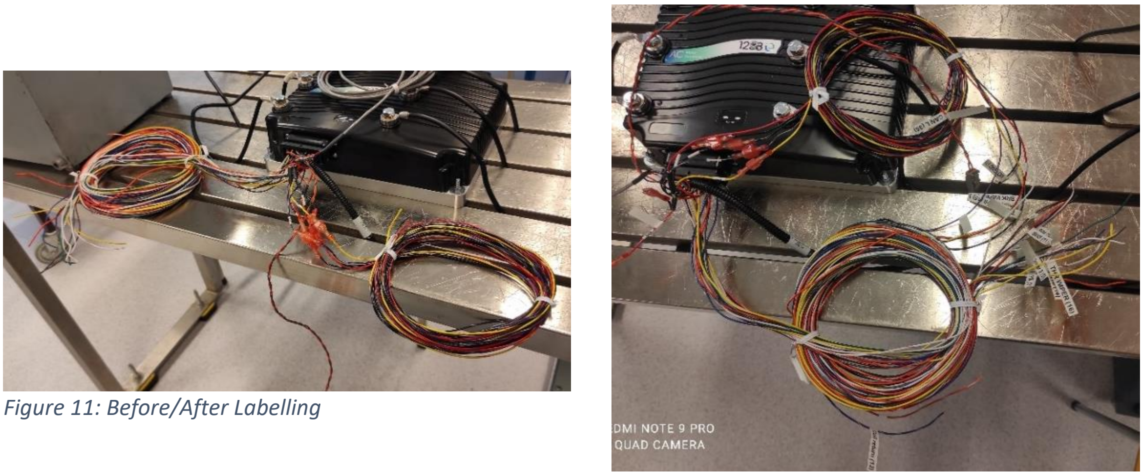


Figure 11: Before/After Labelling

B. Control card

The wiring card will make our life much easier because today, we carry out the first tests on a test bench* and, without this card, we would have had to solder the cables to the different components. This thought of imagining a card was therefore very useful when we had to modify the wiring to add, for example, a component that we could have forgotten.

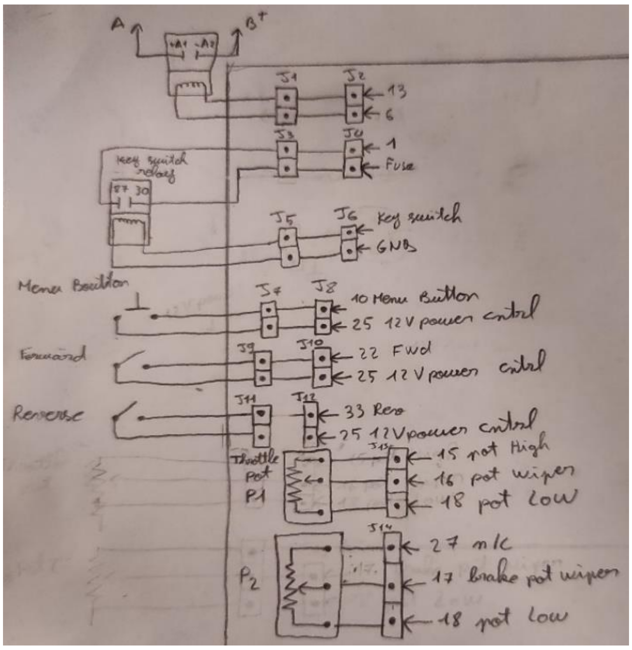


Figure 12: Paper imagination of the card

In order to create this card, we used the different wiring diagrams to propose a first paper version of the schematic (See fig 12).

We quickly moved to something more professional, to propose a cleaner version (See fig 14). Following these various diagrams, the final PCB (Printed Circuit Board*) of the card was finished (See fig 13). However, during the various tests we quickly noticed that we were missing the interlock switch, which we added to the board later.

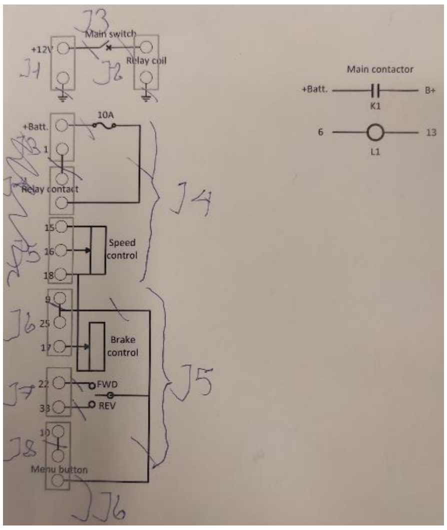


Figure 14: Schematic of the card

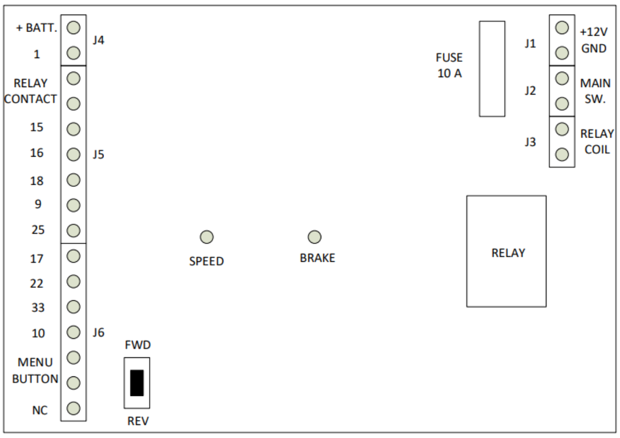


Figure 13: Final PCB

Moreover, the creation of a board in Norway is different from what we can do at Polytech because their board looks like a breadboard* where you have to solder cables in order to create a contact (See fig 15). Finally, to facilitate the wiring/decabling, we put connectors on the cables.

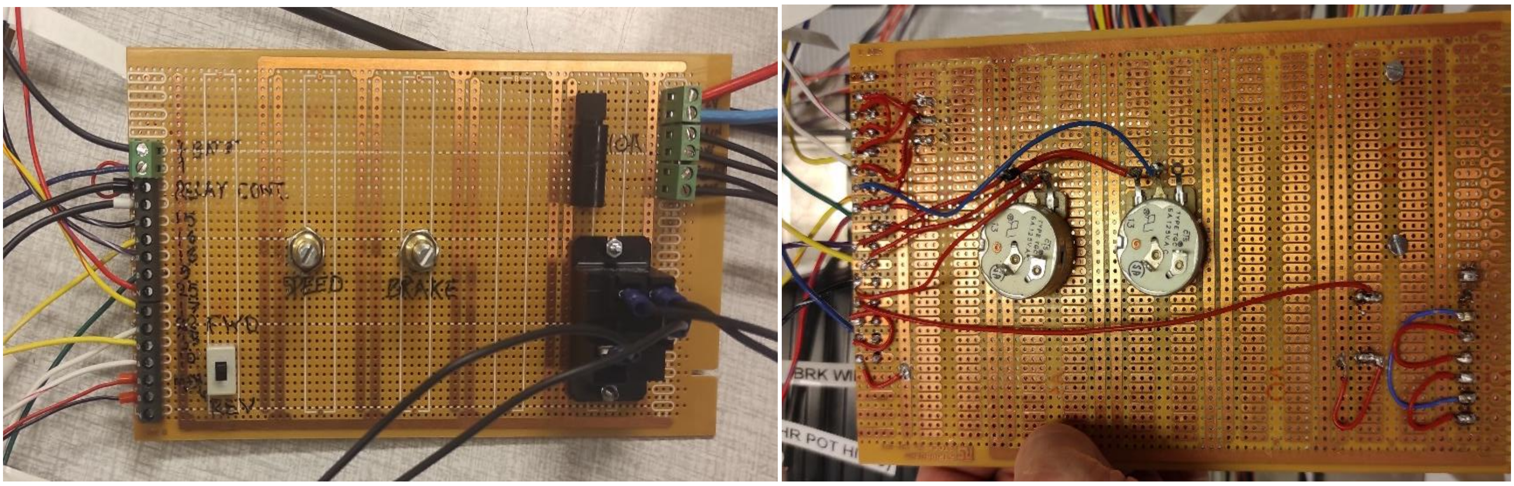


Figure 15: Control Card

IV. Putting in operation

A. Security

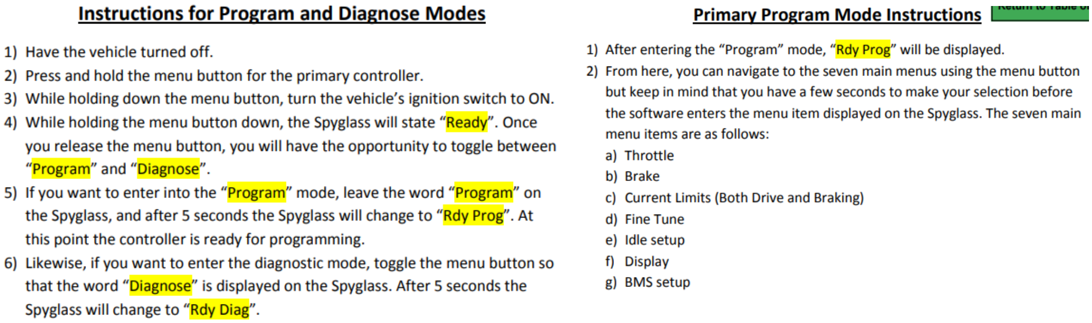
After having managed all the previous parts, the time has come to do the first tests. For that, it is important to make again a point on the safety. Indeed, even if we have protected the connectors with plexiglass* protections, we must not forget that we are handling high current and voltage values. That is why, for all the manipulations, there were two of us and each test/modification is checked by the two actors present during the tests.

To put in operation, we have a generator that we must set to 12V for a part of the circuit. To supply it, we disconnect the generator, we set 12V on it and finally we switch off to reconnect everything.

For the voltage part with a minimum of 48V, the same procedure is followed while checking that everything is respected.

B. Programming

To start the first tests, it is necessary to follow the programming procedure, it should be known that all the programming is done on the small display connected to the controller* (see fig 16). For that, we had in our possession a document which explains point by point how to enter in programming mode (see fig 16), but also how to modify the various parameters which could be useful to us. And finally this document allowed us to enter in diagnostic mode to check some values.



Instructions for Program and Diagnose Modes

1) Have the vehicle turned off.
2) Press and hold the menu button for the primary controller.
3) While holding down the menu button, turn the vehicle's ignition switch to ON.
4) While holding the menu button down, the Spyglass will state "Ready". Once you release the menu button, you will have the opportunity to toggle between "Program" and "Diagnose".
5) If you want to enter into the "Program" mode, leave the word "Program" on the Spyglass, and after 5 seconds the Spyglass will change to "Rdy Prog". At this point the controller is ready for programming.
6) Likewise, if you want to enter the diagnostic mode, toggle the menu button so that the word "Diagnose" is displayed on the Spyglass. After 5 seconds the Spyglass will change to "Rdy Diag".

Primary Program Mode Instructions

1) After entering the "Program" mode, "Rdy Prog" will be displayed.
2) From here, you can navigate to the seven main menus using the menu button but keep in mind that you have a few seconds to make your selection before the software enters the menu item displayed on the Spyglass. The seven main menu items are as follows:
   a) Throttle
   b) Brake
   c) Current Limits (Both Drive and Braking)
   d) Fine Tune
   e) Idle setup
   f) Display
   g) BMS setup

Figure 16: Display and procedures

For the programming, we mainly focused on throttle and brake. For throttle we chose type 3: 5K ohm 3 wire potentiometer with switch, throttle deadband* we got a value of 0.3V, Maximum throttle configured with a value of 5V, finally we have modified the throttle map parameter to about 25% (For brake, we have equivalent values). To have the exact procedures to modify each parameter see annex 3 and 4.

C. Programming and Working test

a. Description of the tests

The first tests were rather simple, at first it was necessary to check that the engine turns, then it was necessary to check if the engine control was functional. In this part, we met several problems, the first one is that the motor did not turn. To manage this problem, we carried out several research, then, we realized that it missed the interlock switch which allowed us to program but also to manage the launching of the motor. We then added this interlock switch, and we did another time all the programming. This switch allowed us to program the deathband* of the potentiometers* as well as its maximum value. We had then coherent values: 5V for the max Value and 0.3V for the deathband* (Without interlock switch we had incoherent values 5V for the deathband* and the max Value for example).

After having managed the above points, the motor was then functional (in both directions). It is important to add that we can also manage the Speed of the motor but only on the range 0-950 RPM (Revolution Per Minute). When we exceed 950-1000 RPM the modification is not functional anymore. While searching, we suspect that there are parameters that can only be programmed with the programming module, which we do not have at the moment.

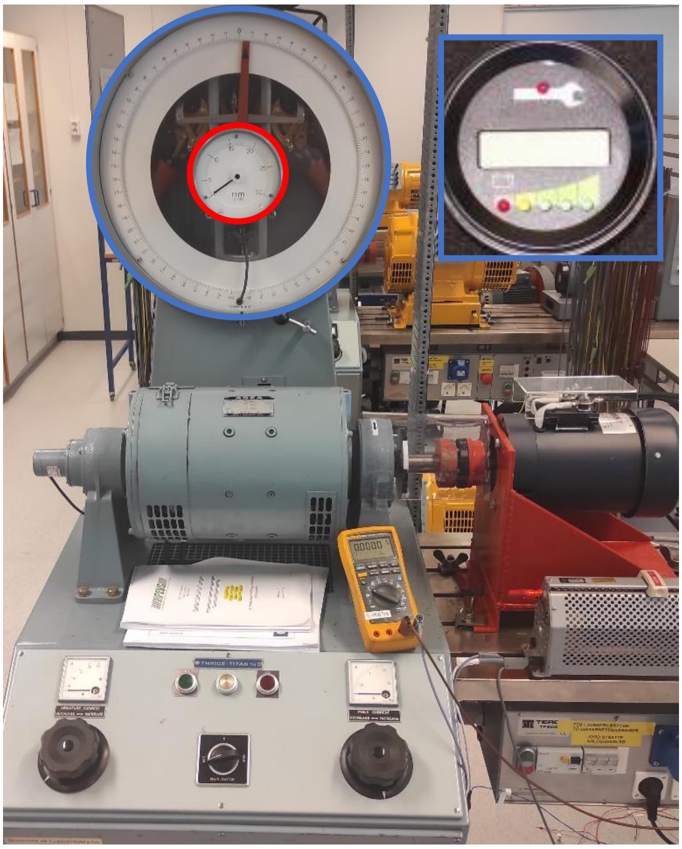
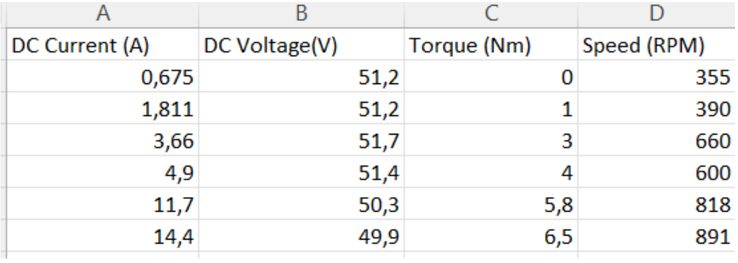


Figure 17: Machine auxiliaire (type banc d'essai)

Finally, we arrive on tests where we will recover values which will be able to be analyzed in the next point. For these tests, we are going to connect our engine to an auxiliary machine (See fig) which can add torque* and/or speed with modes (generator or motor). Our tests will be carried out with the auxiliary machine in generator mode. We recovered the values of the DC (Direct Current) current (A) and voltage (V) using a multimeter and a current clamp. We also recovered the value of the torque* (Nm (Newton meter)) and the speed (RPM), the value of the torque is given by the red dial and the speed by the blue dial but also by the display of the controller* (on figure 17). The manipulation is simple, we have carried out the start-up with as always a careful check. Then we obtained different values by increasing the speed as well as the torque* (See fig 18).



A	B	C	D
DC Current (A)	DC Voltage(V)	Torque (Nm)	Speed (RPM)
0,675	51,2	0	355
1,811	51,2	1	390
3,66	51,7	3	660
4,9	51,4	4	600
11,7	50,3	5,8	818
14,4	49,9	6,5	891

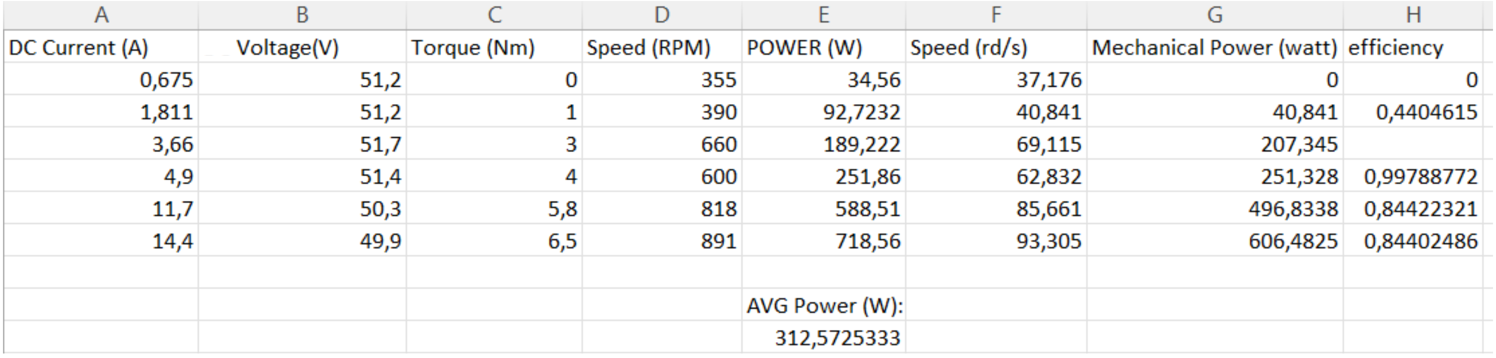
Figure 18: Test chart

b. Test analysis

With the tests, we have recovered several values like the DC current, DC voltage, the resisting torque that we will apply to have a more real approach, the speed and finally we will calculate the power (electrical and mechanical).

Figure 19: Equipment for current and voltage recovery

Here is the table of values that we could recover with in addition the powers (Voir fig):



A	B	C	D	E	F	G	H
DC Current (A)	Voltage(V)	Torque (Nm)	Speed (RPM)	POWER (W)	Speed (rd/s)	Mechanical Power (watt)	efficiency
0,675	51,2	0	355	34,56	37,176	0	0
1,811	51,2	1	390	92,7232	40,841	40,841	0,4404615
3,66	51,7	3	660	189,222	69,115	207,345	
4,9	51,4	4	600	251,86	62,832	251,328	0,99788772
11,7	50,3	5,8	818	588,51	85,661	496,8338	0,84422321
14,4	49,9	6,5	891	718,56	93,305	606,4825	0,84402486
				AVG Power (W):			
				312,5725333			

Figure 20: Table of test values

At first, we can see that we have not exceeded 900 RPM, as explained in the previous summary, above that we are not very precise when we modify the speed.

Moreover, for a question of security the equipment that we have used should not exceed 1700-2000 RPM (max).

We have drawn a graph (see fig 22) showing the power as a function of the torque* (Nm) and a graph (see fig 21) showing the power as a function of the speed (RPM).

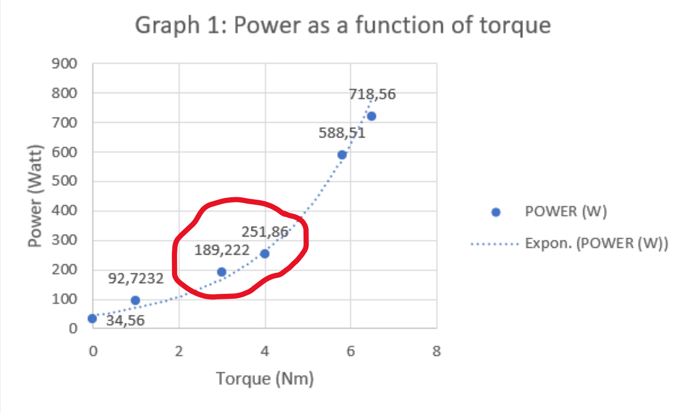


Figure 22: Power as a function of torque

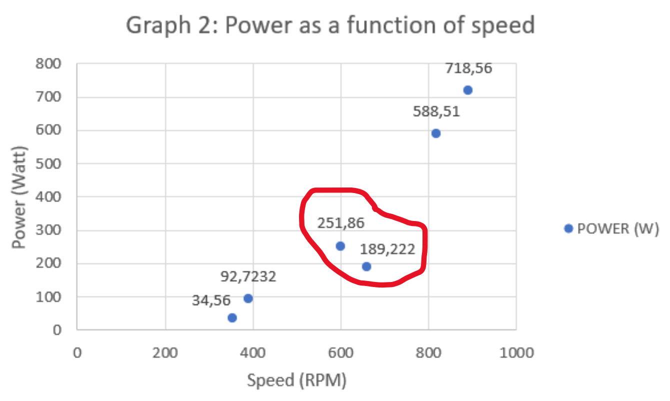
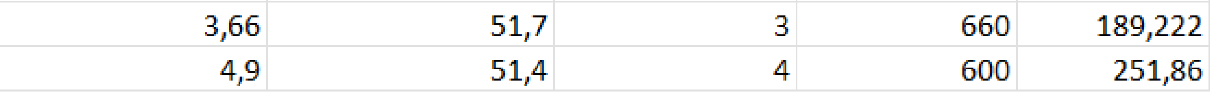


Figure 21: Power as a function of speed

We see with the 2 graphs that when we increase the torque*, the power will increase even if the speed is lower than the previous speed (In our case see the figure 23).



3,66	51,7	3	660	189,222
4,9	51,4	4	600	251,86

Figure 23: Interesting values

Here, we see that we have a lower speed (660 -> 600) however our power is greater. So, the more torque* we have, the more energy we will consume. For the speed it is globally the same things more we will want to go fast, more we will consume (but not always).

Finally, we see that our current increases (0,675-14.4 A), according to our speed and our torque* while our voltage it slightly decreases (2-3 V).

We can then calculate the average power of our different tests (312 W) with the equation Electrical Power (Pelec)=Idc*Udc. This value can enlighten us on our consumption and finally it will be used to choose batteries.

We can also have the mechanical power with the equation Mechanical Power (pm)=C*Ω. This allows us to calculate the efficiency with the equation η=Pm/Pelec. We observe on the table above (see fig 20) that our efficiency is rather correct.

V. To be continued

In this part, we are going to propose a placement of the various equipment within the snowmobile with the help of diagrams. These diagrams will allow in the future to have a first vision of things and to imagine an installation which remains coherent today.

A. Equipment placement diagram

We propose you below a drawing of the snowmobile with all the useful measurements (see fig 24). On the drawing the orange arrows represent the height, for the height =550mm, it is the highest point.

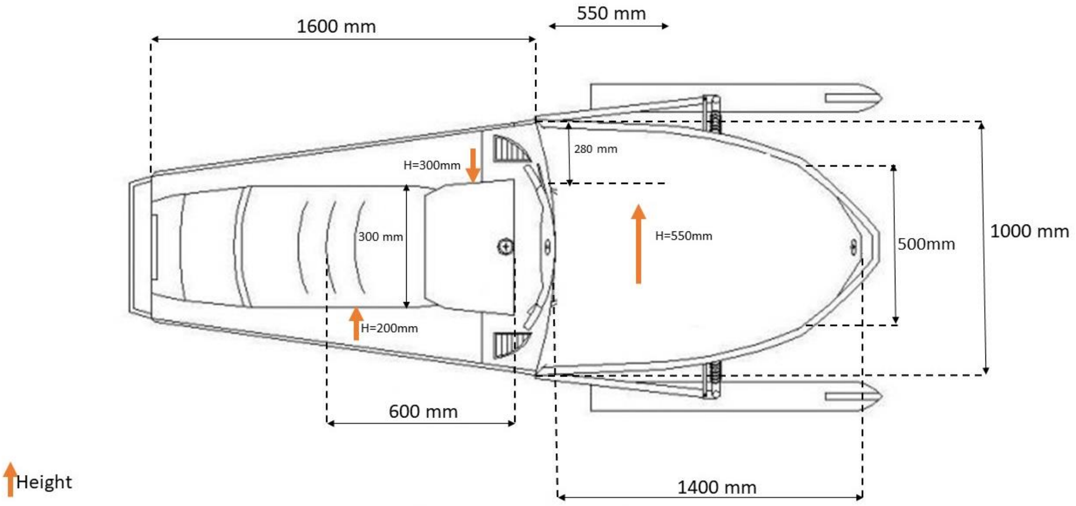
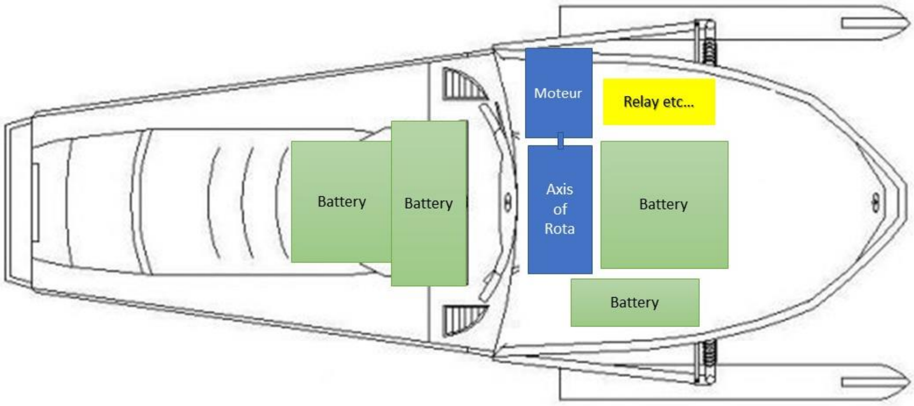


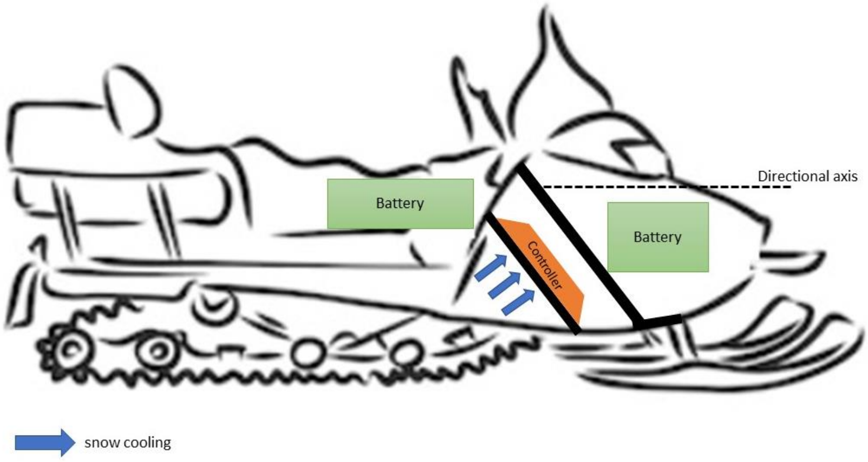
Figure 24: Dimensional drawing

Here is a diagram that allows us to imagine how we see the placement of the material within the snowmobile (see fig 25 and 26).



In this case, we imagine the engine on the side however by measuring, we notice that it will not fit unless we imagine a slight modification of the body of our snowmobile (which is actually our best solution).

Figure 25: Top view diagram



For the controller*, we would like to place it as close as possible to the belt of the snowmobile in order to benefit from an optimal cooling (see fig 26). We will be able to define the exact location of this one when all the useless equipment will be removed.

Figure 26: Side view diagram

Finally, the other locations seem to be coherent, and the measurements confirm my choices with the possibility of arranging different places for the batteries (4 slots) or material.

B. Battery suggestion

For our battery, we did not choose the method that we wanted to use. Several choices are available to us, the first take the battery that are proposed by the site where was purchased the controller (in this case modules tesla), but they are currently unavailable. We can otherwise find a battery that suits us on the internet however we should be careful regarding the size of it (positive point of this proposal, they often have the BMS (Battery Management System*) etc. ...) and finally the last possibility is to buy battery cells in order to arrange them as desired in the snowmobile (You will find different battery options in the appendix 5,6,7 and 8).

VI. Conclusion

A. Professional conclusion

To conclude this project, the problem has been treated for the most part:

- We can run the engine globally correctly.
- We have greatly facilitated the wiring through the implementation of labels, but also by creating the control card.
- We have made some tests to have a more real image of our installation (to understand how it works …).
- We also proposed an organization of the equipment in the snowmobile that could be useful in the future.
- In addition, a suggestion of different batteries in the appendix will probably make it easier to choose the good one.

Finally, this project of fourth year of engineering school was in perfect adequacy with my current school curriculum. Indeed, this project gathers different domains of electrical engineering on which I could already work. For me, to apply some things that I learned during my studies is a real satisfaction.

B. Personal conclusion

During my fourth year at POLYTECH Clermont, I had the opportunity to do an internship abroad for 4 months at the UIT Norges Artic university in Narvik. I chose this university because I wanted to discover a completely different culture and thus benefit from a total change of environment. Moreover, I found it judicious to discover such a part of the world which is known to work on the fields of energy, knowing that I would like to continue in this sector.

This 4-month internship was very enriching and taught me a lot; I was able to apply the knowledge acquired during my years of study. This knowledge, both technical and practical, was a great help to me. This experience has changed my vision of the world but not only that, I have modified my way of working and thinking. Moreover, a new vision of security appeared, I really became aware of the necessity to pay attention to all the equipment and to myself. I was also able to realize the work to be done as well as the qualities to be possessed (critical spirit, organizational, methodical, motivation).

This internship has been a real opportunity for my professional and personal experience. Although I was confronted with the limits of time and resources, this internship also allowed me to realize my own limits and points to improve for the future. Despite these difficulties, this experience has largely met my expectations and I was enthusiastic about these 4 months spent with a welcoming and attentive staff and I thank them once again.

VII. Cultural openness

First of all, one thing impressed me, the work atmosphere which is just perfect. Indeed, everything is turned around the “well-being”, we quickly notice that there are sofas with tables everywhere to take advantage of the breaks (to decompress). For the more athletic, there are sports activities at specific times, for example soccer which I immediately participated in. There are also ping pong tables to spend time with friends. Not to forget the workrooms which are very well equipped, I worked in a welding laboratory, and I was impressed by the quality of the equipment. I was pleasantly surprised by the attention to safety, because in each laboratory they provide first aid kits ... We note in addition, the presence of a sports hall stuck to the university offering the opportunity to students to practice sports at any time of day.

An important point that we don't find very often in France is the benevolence, the respect, and the open-mindedness of each person we have met. They have always been in the sharing and the desire to know us and that allowed me to open up to people, to make encounters (following this, I already plan to travel in their countries but also to make them discover mine). They are also super invested in everything they do, if I had to give a striking example it's the buses that are on time or even in advance every time. Moreover, their pedestrian light button is completely functional. I would also add that when approaching the pedestrian crossings, the drivers are very courteous.

What shocked me the most, I think, was the cold and the thick layer of snow when I arrived. I think I will never forget the first day. I had to drag my suitcase all the way up the mountain to get to my apartment (terrifying on paper but worse in real life). A point not to be neglected is the cost of living which is easily twice as expensive as in France (an example, the hairdresser 20€ in France and 60€ in Norway (I didn't go there, so know I look like a Gremlins)). The landscape however remains amazing and offers a total change of environment.

Finally, I will add one last thing that affected me a lot, it is that from mid-May the day was present constantly. Moreover, their lights are all the time switch on which is not at all the case in France (they did not understand “c’est pas Versaille ici”).

VIII. References

[1] evwest.com « Battery Tesla module » [website] :

https://www.evwest.com/catalog/product_info.php?cPath=4&products_id=329&osCsid=jbqvenv7jviocgmk0j4p0s4do6

[2] wxaobocs.en.made-in-china.com « EV Power Lithium Battery » [website] :

https://wxaobocs.en.made-in-china.com/product/ownJeqPYhDWl/China-72V-200ah-Lithium-Ion-Battery-for-Golf-Cart.html

[3] evwest.com « ELCON PFC1500 Charger » [website] :

https://www.evwest.com/catalog/product_info.php?cPath=12&products_id=247&osCsid=f4a5982c45c8c4fe2ee23fad18f16478

[4] evwest.com « J1772 32A Receptacle » [website] :

https://www.evwest.com/catalog/product_info.php?cPath=12&products_id=247&osCsid=f4a5982c45c8c4fe2ee23fad18f16478

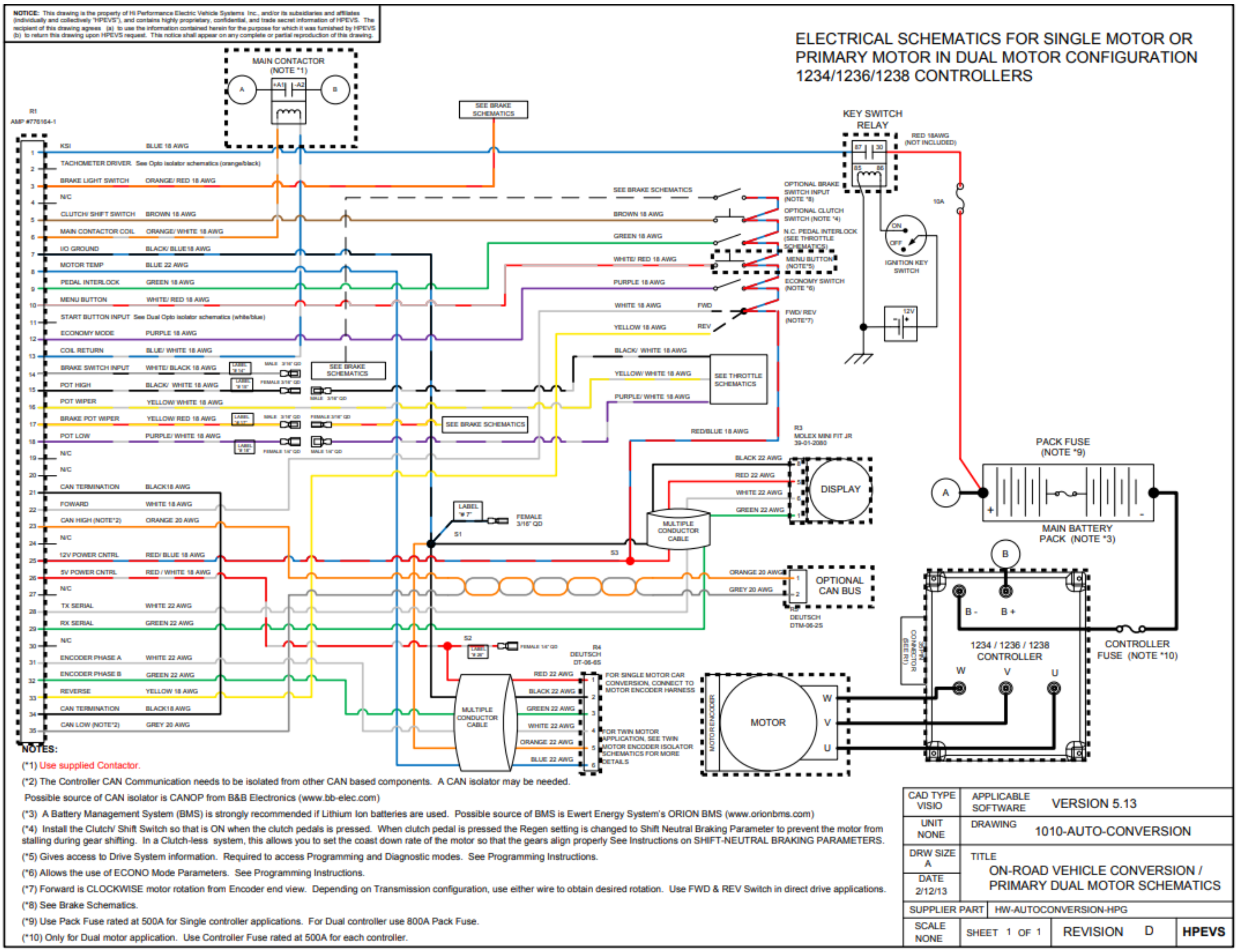
[5] evwest.com « J1772 Active vehicle control module AVC2 » [website] :

https://www.evwest.com/catalog/product_info.php?cPath=12&products_id=247&osCsid=f4a5982c45c8c4fe2ee23fad18f16478

Table of appendix

IX. Appendix

Appendix 1: Electrical schematics



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ELECTRICAL SCHEMATICS FOR SINGLE MOTOR OR PRIMARY MOTOR IN DUAL MOTOR CONFIGURATION 1234/1236/1238 CONTROLLERS

NOTES:

(*1) Use supplied Contactor.

(*2) The Controller CAN Communication needs to be isolated from other CAN based components. A CAN isolator may be needed.
Possible source of CAN isolator is CANOP from B&B Electronics (www.bb-elec.com)

(*3) A Battery Management System (BMS) is strongly recommended if Lithium Ion batteries are used. Possible source of BMS is Ewert Energy System's ORION BMS (www.orionbms.com)

(*4) Install the Clutch/ Shift Switch so that is ON when the clutch pedals is pressed. When clutch pedal is pressed the Regen setting is changed to Shift Neutral Braking Parameter to prevent the motor from stalling during gear shifting. In a Clutch-less system, this allows you to set the coast down rate of the motor so that the gears align properly See Instructions on SHIFT-NEUTRAL BRAKING PARAMETERS.

(*5) Gives access to Drive System information. Required to access Programming and Diagnostic modes. See Programming Instructions.

(*6) Allows the use of ECONO Mode Parameters. See Programming Instructions.

(*7) Forward is CLOCKWISE motor rotation from Encoder end view. Depending on Transmission configuration, use either wire to obtain desired rotation. Use FWD & REV Switch in direct drive applications.

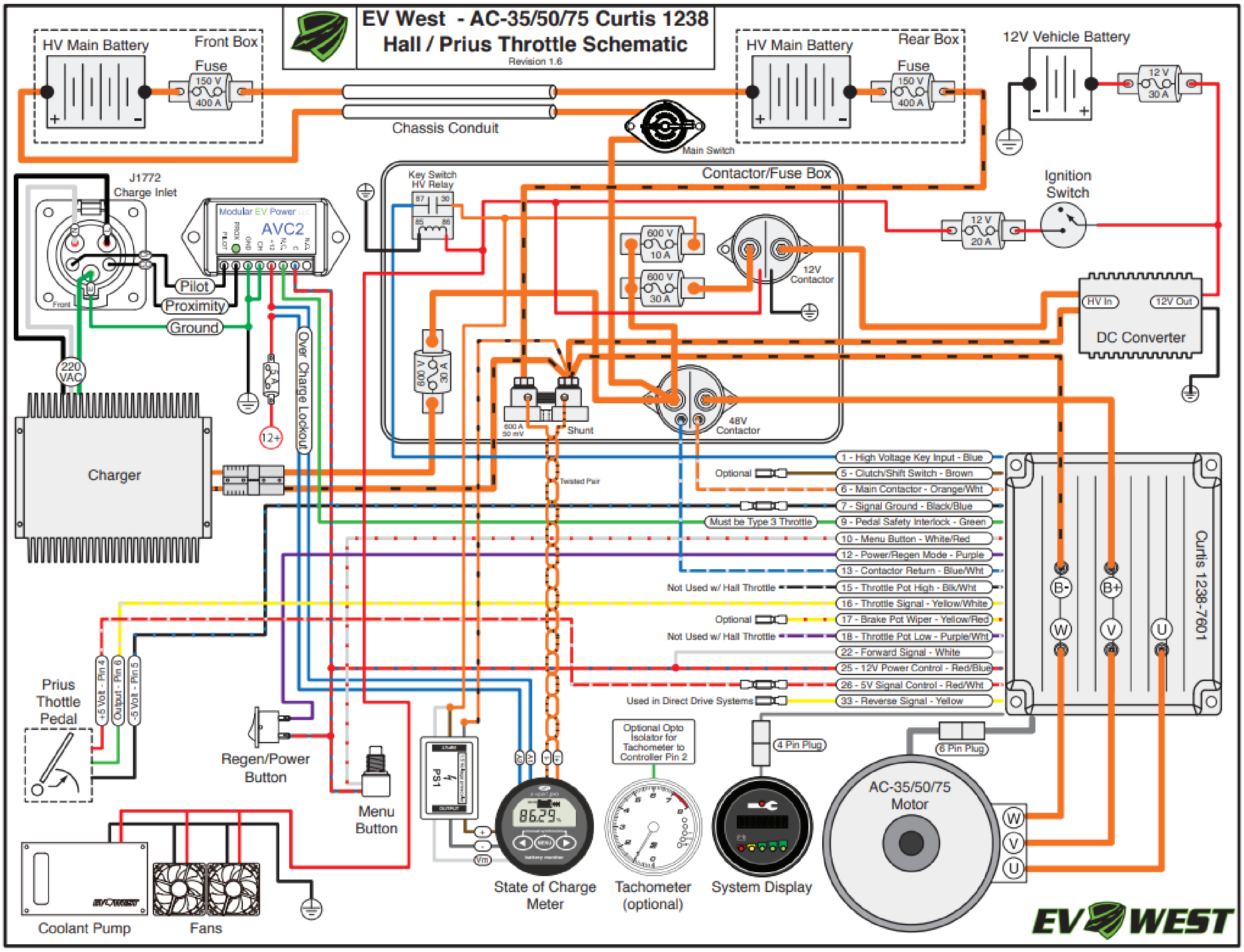
(*8) See Brake Schematics.

(*9) Use Pack Fuse rated at 500A for Single controller applications. For Dual controller use 800A Pack Fuse.

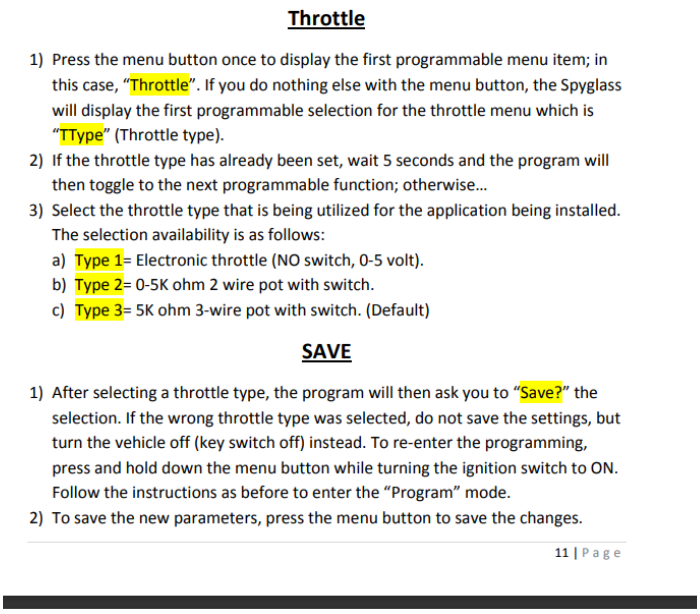
(*10) Only for Dual motor application. Use Controller Fuse rated at 500A for each controller.

CAD TYPE VISIO	APPLICABLE SOFTWARE	VERSION 5.13
UNIT NONE	DRAWING	1010-AUTO-CONVERSION
DRW SIZE A DATE 2/12/13	TITLE	ON-ROAD VEHICLE CONVERSION / PRIMARY DUAL MOTOR SCHEMATICS
SUPPLIER PART		HW-AUTOCONVERSION-HPG
SCALE NONE	SHEET 1 OF 1	REVISION D HPEVS

Appendix 2: Electrical schematics



Appendix 3: Programming procedure



Throttle

1) Press the menu button once to display the first programmable menu item; in this case, "Throttle". If you do nothing else with the menu button, the Spyglass will display the first programmable selection for the throttle menu which is "TType" (Throttle type).
2) If the throttle type has already been set, wait 5 seconds and the program will then toggle to the next programmable function; otherwise…
3) Select the throttle type that is being utilized for the application being installed. The selection availability is as follows:
   a) Type 1= Electronic throttle (NO switch, 0-5 volt).
   b) Type 2= 0-5K ohm 2 wire pot with switch.
   c) Type 3= 5K ohm 3-wire pot with switch. (Default)

SAVE

1) After selecting a throttle type, the program will then ask you to "Save?" the selection. If the wrong throttle type was selected, do not save the settings, but turn the vehicle off (key switch off) instead. To re-enter the programming, press and hold down the menu button while turning the ignition switch to ON. Follow the instructions as before to enter the "Program" mode.
2) To save the new parameters, press the menu button to save the changes.

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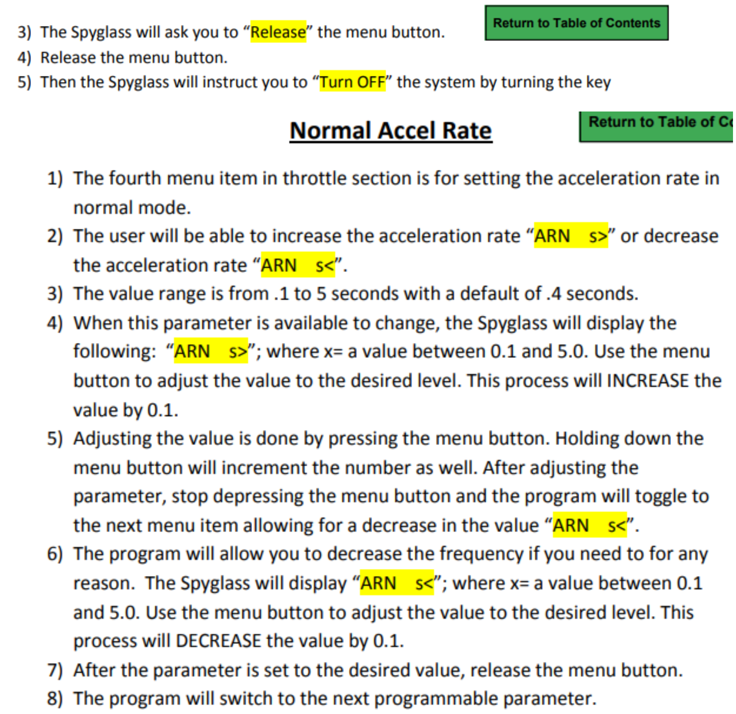


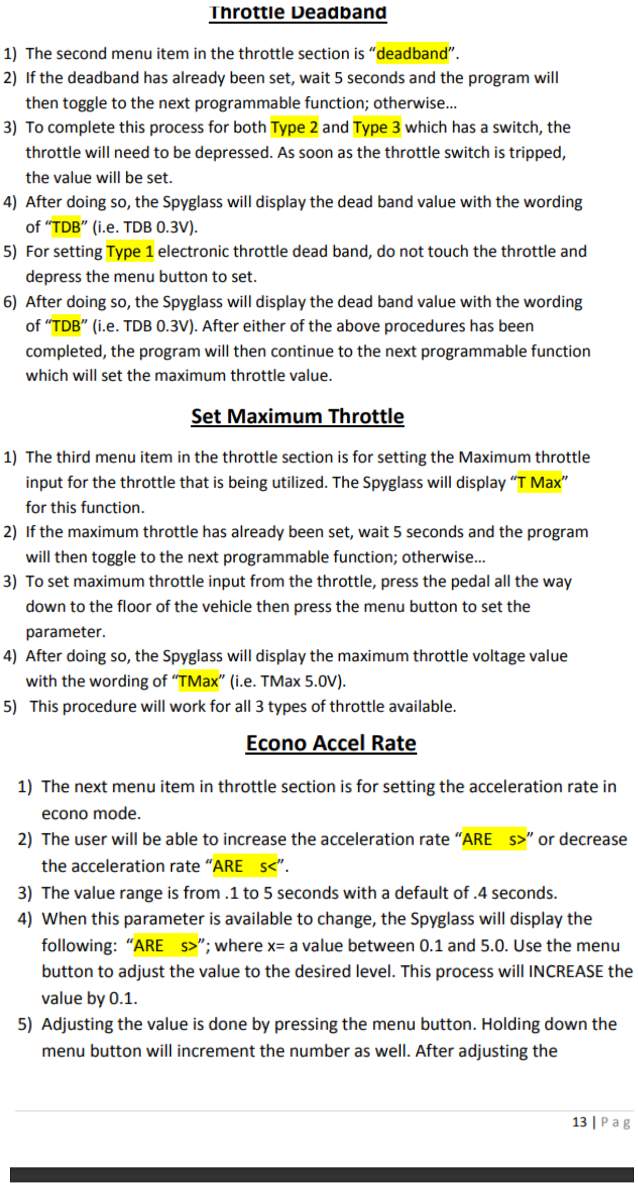
Return to Table of Contents

3) The Spyglass will ask you to "Release" the menu button.
4) Release the menu button.
5) Then the Spyglass will instruct you to "Turn OFF" the system by turning the key

Normal Accel Rate

Return to Table of C

1) The fourth menu item in throttle section is for setting the acceleration rate in normal mode.
2) The user will be able to increase the acceleration rate "ARN s>" or decrease the acceleration rate "ARN s<".
3) The value range is from .1 to 5 seconds with a default of .4 seconds.
4) When this parameter is available to change, the Spyglass will display the following: "ARN s>"; where x= a value between 0.1 and 5.0. Use the menu button to adjust the value to the desired level. This process will INCREASE the value by 0.1.
5) Adjusting the value is done by pressing the menu button. Holding down the menu button will increment the number as well. After adjusting the parameter, stop depressing the menu button and the program will toggle to the next menu item allowing for a decrease in the value "ARN s<".
6) The program will allow you to decrease the frequency if you need to for any reason. The Spyglass will display "ARN s<"; where x= a value between 0.1 and 5.0. Use the menu button to adjust the value to the desired level. This process will DECREASE the value by 0.1.
7) After the parameter is set to the desired value, release the menu button.
8) The program will switch to the next programmable parameter.



Throttle Deadband

1) The second menu item in the throttle section is "deadband".
2) If the deadband has already been set, wait 5 seconds and the program will then toggle to the next programmable function; otherwise…
3) To complete this process for both Type 2 and Type 3 which has a switch, the throttle will need to be depressed. As soon as the throttle switch is tripped, the value will be set.
4) After doing so, the Spyglass will display the dead band value with the wording of "TDB" (i.e. TDB 0.3V).
5) For setting Type 1 electronic throttle dead band, do not touch the throttle and depress the menu button to set.
6) After doing so, the Spyglass will display the dead band value with the wording of "TDB" (i.e. TDB 0.3V). After either of the above procedures has been completed, the program will then continue to the next programmable function which will set the maximum throttle value.

Set Maximum Throttle

1) The third menu item in the throttle section is for setting the Maximum throttle input for the throttle that is being utilized. The Spyglass will display "T Max" for this function.
2) If the maximum throttle has already been set, wait 5 seconds and the program will then toggle to the next programmable function; otherwise…
3) To set maximum throttle input from the throttle, press the pedal all the way down to the floor of the vehicle then press the menu button to set the parameter.
4) After doing so, the Spyglass will display the maximum throttle voltage value with the wording of "TMax" (i.e. TMax 5.0V).
5) This procedure will work for all 3 types of throttle available.

Econo Accel Rate

1) The next menu item in throttle section is for setting the acceleration rate in econo mode.
2) The user will be able to increase the acceleration rate "ARE s>" or decrease the acceleration rate "ARE s<".
3) The value range is from .1 to 5 seconds with a default of .4 seconds.
4) When this parameter is available to change, the Spyglass will display the following: "ARE s>"; where x= a value between 0.1 and 5.0. Use the menu button to adjust the value to the desired level. This process will INCREASE the value by 0.1.
5) Adjusting the value is done by pressing the menu button. Holding down the menu button will increment the number as well. After adjusting the

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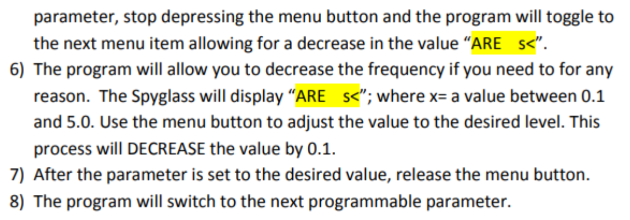
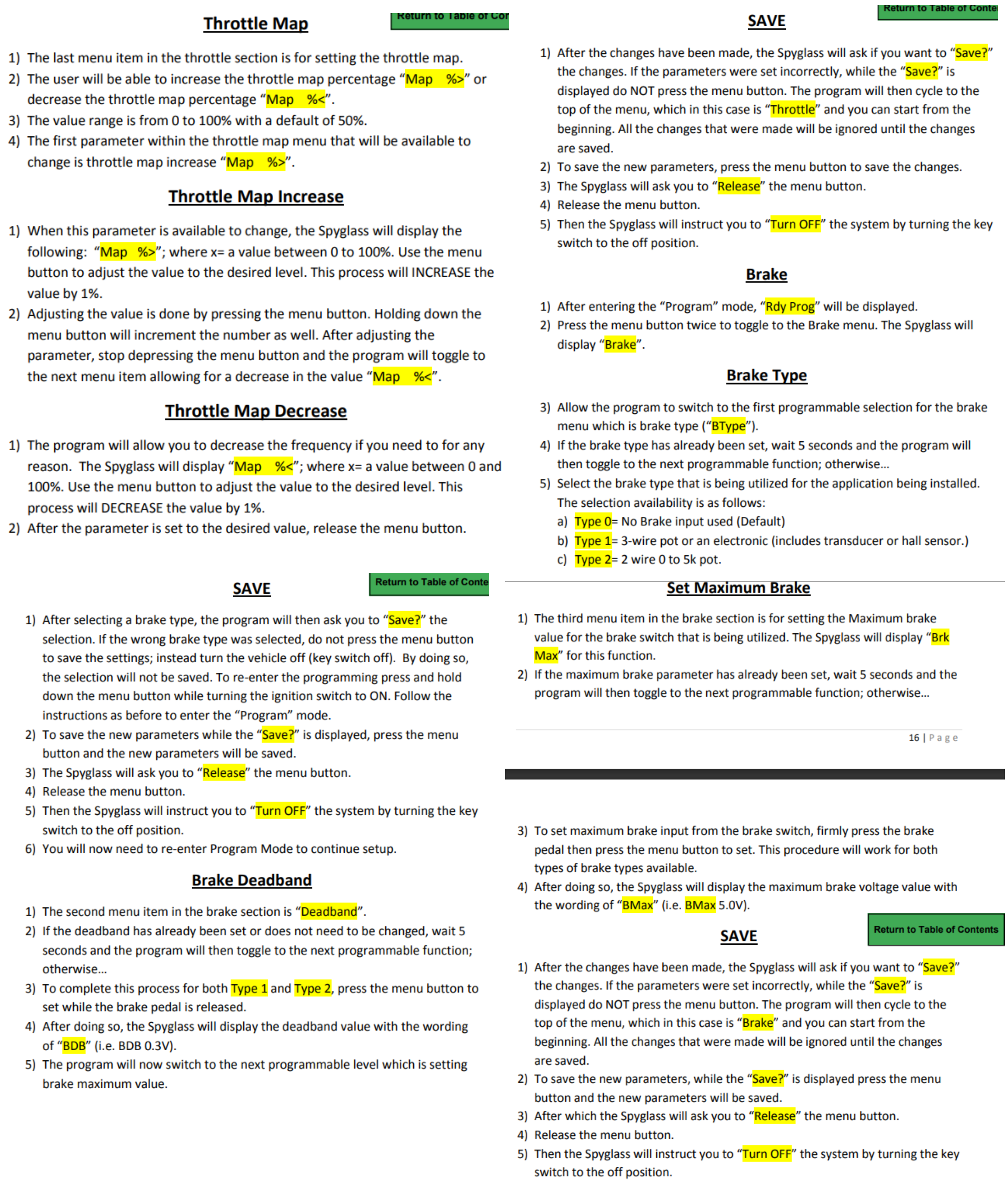


parameter, stop depressing the menu button and the program will toggle to the next menu item allowing for a decrease in the value "ARE s<".

6) The program will allow you to decrease the frequency if you need to for any reason. The Spyglass will display "ARE s<"; where x= a value between 0.1 and 5.0. Use the menu button to adjust the value to the desired level. This process will DECREASE the value by 0.1.
7) After the parameter is set to the desired value, release the menu button.
8) The program will switch to the next programmable parameter.

Appendix 4: Programming procedure



Throttle Map

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1) The last menu item in the throttle section is for setting the throttle map.
2) The user will be able to increase the throttle map percentage "Map %>" or decrease the throttle map percentage "Map %<".
3) The value range is from 0 to 100% with a default of 50%.
4) The first parameter within the throttle map menu that will be available to change is throttle map increase "Map %>".

Throttle Map Increase

1) When this parameter is available to change, the Spyglass will display the following: "Map %>"; where x= a value between 0 to 100%. Use the menu button to adjust the value to the desired level. This process will INCREASE the value by 1%.
2) Adjusting the value is done by pressing the menu button. Holding down the menu button will increment the number as well. After adjusting the parameter, stop depressing the menu button and the program will toggle to the next menu item allowing for a decrease in the value "Map %<".

Throttle Map Decrease

1) The program will allow you to decrease the frequency if you need to for any reason. The Spyglass will display "Map %<"; where x= a value between 0 and 100%. Use the menu button to adjust the value to the desired level. This process will DECREASE the value by 1%.
2) After the parameter is set to the desired value, release the menu button.

SAVE

Return to Table of Conte

1) After selecting a brake type, the program will then ask you to "Save?" the selection. If the wrong brake type was selected, do not press the menu button to save the settings; instead turn the vehicle off (key switch off). By doing so, the selection will not be saved. To re-enter the programming press and hold down the menu button while turning the ignition switch to ON. Follow the instructions as before to enter the "Program" mode.
2) To save the new parameters while the "Save?" is displayed, press the menu button and the new parameters will be saved.
3) The Spyglass will ask you to "Release" the menu button.
4) Release the menu button.
5) Then the Spyglass will instruct you to "Turn OFF" the system by turning the key switch to the off position.
6) You will now need to re-enter Program Mode to continue setup.

Brake Deadband

1) The second menu item in the brake section is "Deadband".
2) If the deadband has already been set or does not need to be changed, wait 5 seconds and the program will then toggle to the next programmable function; otherwise…
3) To complete this process for both Type 1 and Type 2, press the menu button to set while the brake pedal is released.
4) After doing so, the Spyglass will display the deadband value with the wording of "BDB" (i.e. BDB 0.3V).
5) The program will now switch to the next programmable level which is setting brake maximum value.

SAVE

Return to Table of Conte

1) After the changes have been made, the Spyglass will ask if you want to "Save?" the changes. If the parameters were set incorrectly, while the "Save?" is displayed do NOT press the menu button. The program will then cycle to the top of the menu, which in this case is "Throttle" and you can start from the beginning. All the changes that were made will be ignored until the changes are saved.
2) To save the new parameters, press the menu button to save the changes.
3) The Spyglass will ask you to "Release" the menu button.
4) Release the menu button.
5) Then the Spyglass will instruct you to "Turn OFF" the system by turning the key switch to the off position.

Brake

1) After entering the "Program" mode, "Rdy Prog" will be displayed.
2) Press the menu button twice to toggle to the Brake menu. The Spyglass will display "Brake".

Brake Type

3) Allow the program to switch to the first programmable selection for the brake menu which is brake type ("BType").
4) If the brake type has already been set, wait 5 seconds and the program will then toggle to the next programmable function; otherwise…
5) Select the brake type that is being utilized for the application being installed. The selection availability is as follows:
   a) Type 0= No Brake input used (Default)
   b) Type 1= 3-wire pot or an electronic (includes transducer or hall sensor.)
   c) Type 2= 2 wire 0 to 5k pot.

Set Maximum Brake

1) The third menu item in the brake section is for setting the Maximum brake value for the brake switch that is being utilized. The Spyglass will display "Brk Max" for this function.
2) If the maximum brake parameter has already been set, wait 5 seconds and the program will then toggle to the next programmable function; otherwise…

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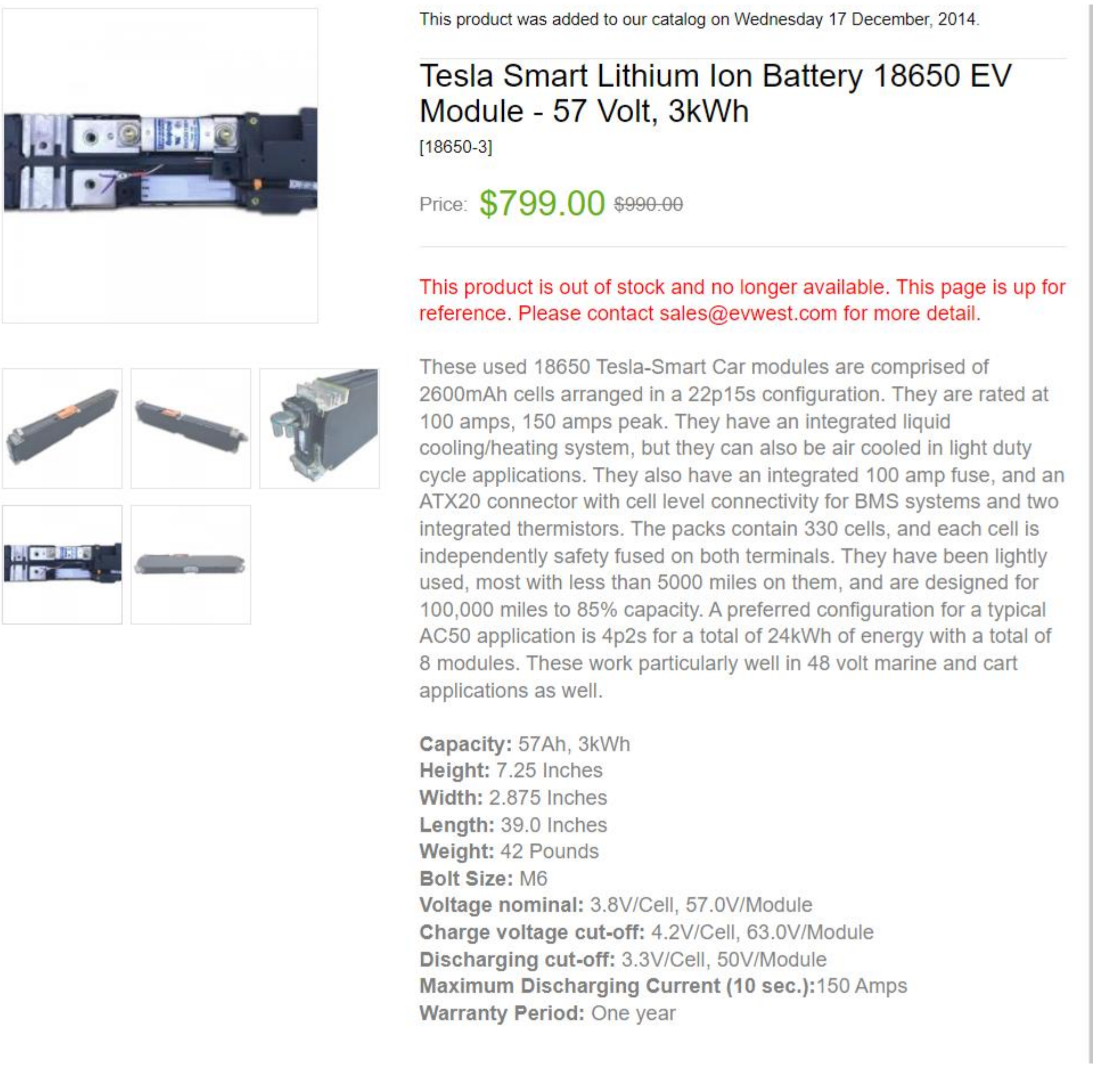
3) To set maximum brake input from the brake switch, firmly press the brake pedal then press the menu button to set. This procedure will work for both types of brake types available.
4) After doing so, the Spyglass will display the maximum brake voltage value with the wording of "BMax" (i.e. BMax 5.0V).

SAVE

Return to Table of Contents

1) After the changes have been made, the Spyglass will ask if you want to "Save?" the changes. If the parameters were set incorrectly, while the "Save?" is displayed do NOT press the menu button. The program will then cycle to the top of the menu, which in this case is "Brake" and you can start from the beginning. All the changes that were made will be ignored until the changes are saved.
2) To save the new parameters, while the "Save?" is displayed press the menu button and the new parameters will be saved.
3) After which the Spyglass will ask you to "Release" the menu button.
4) Release the menu button.
5) Then the Spyglass will instruct you to "Turn OFF" the system by turning the key switch to the off position.

Appendix 5: Battery Tesla Module [1]



This product was added to our catalog on Wednesday 17 December, 2014.

Tesla Smart Lithium Ion Battery 18650 EV Module - 57 Volt, 3kWh

[18650-3]

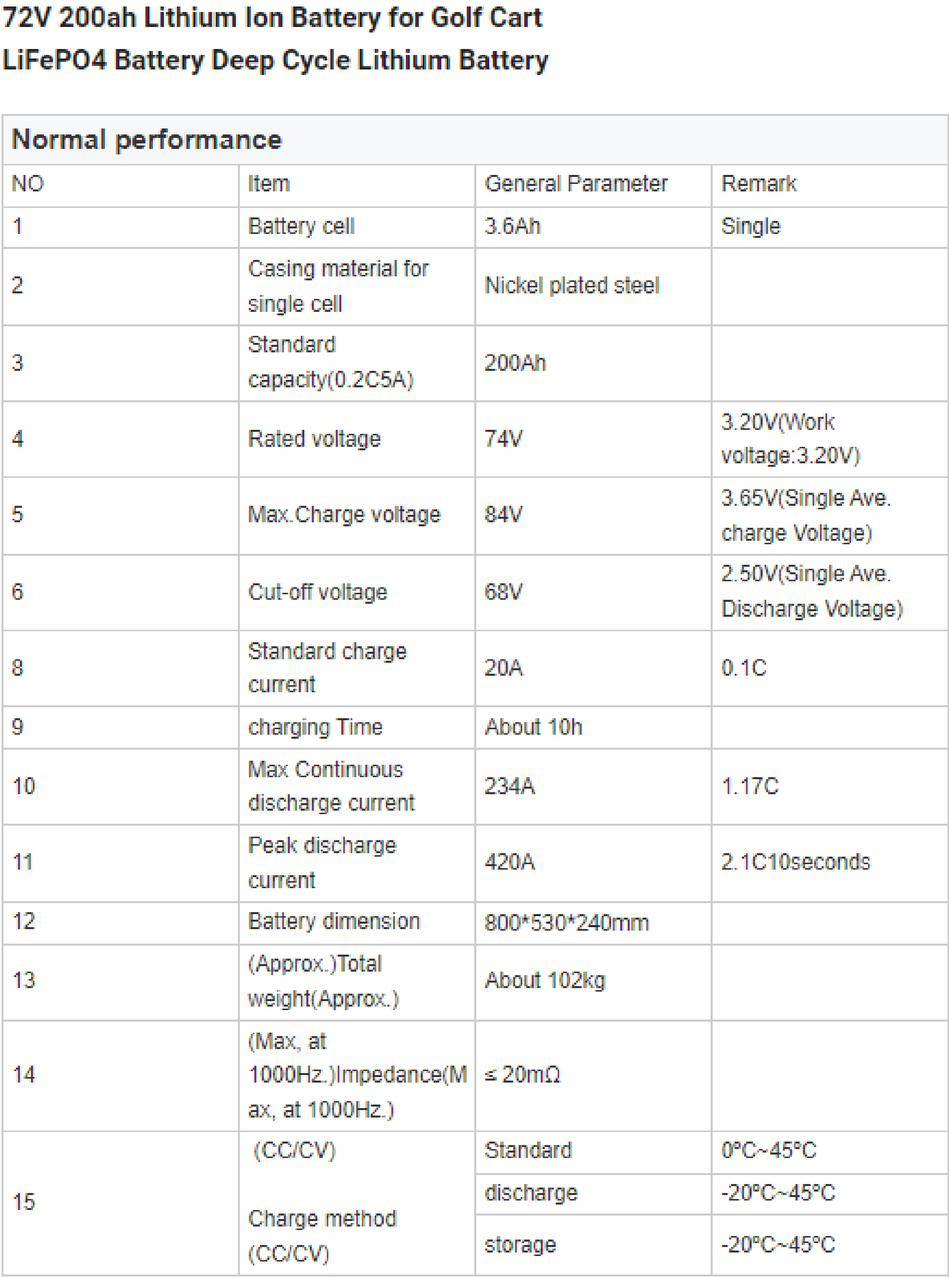
Price: $799.00 ~~$990.00~~

This product is out of stock and no longer available. This page is up for reference. Please contact sales@evwest.com for more detail.

These used 18650 Tesla-Smart Car modules are comprised of 2600mAh cells arranged in a 22p15s configuration. They are rated at 100 amps, 150 amps peak. They have an integrated liquid cooling/heating system, but they can also be air cooled in light duty cycle applications. They also have an integrated 100 amp fuse, and an ATX20 connector with cell level connectivity for BMS systems and two integrated thermistors. The packs contain 330 cells, and each cell is independently safety fused on both terminals. They have been lightly used, most with less than 5000 miles on them, and are designed for 100,000 miles to 85% capacity. A preferred configuration for a typical AC50 application is 4p2s for a total of 24kWh of energy with a total of 8 modules. These work particularly well in 48 volt marine and cart applications as well.

Capacity: 57Ah, 3kWh
Height: 7.25 Inches
Width: 2.875 Inches
Length: 39.0 Inches
Weight: 42 Pounds
Bolt Size: M6
Voltage nominal: 3.8V/Cell, 57.0V/Module
Charge voltage cut-off: 4.2V/Cell, 63.0V/Module
Discharging cut-off: 3.3V/Cell, 50V/Module
Maximum Discharging Current (10 sec.):150 Amps
Warranty Period: One year

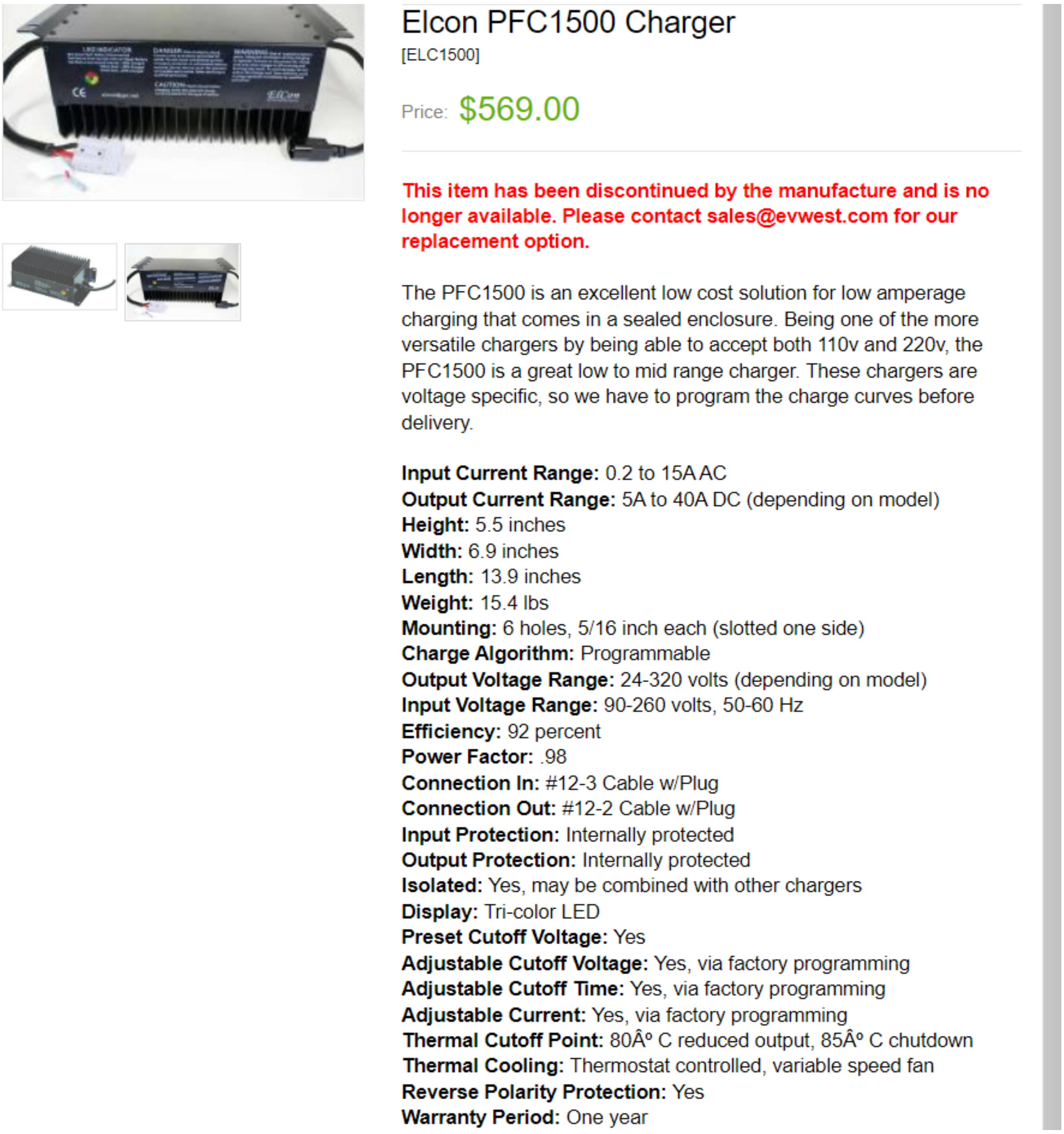
Appendix 6: EV Power Lithium Battery [2]



72V 200ah Lithium Ion Battery for Golf Cart LiFePO4 Battery Deep Cycle Lithium Battery

Normal performance			
NO	Item	General Parameter	Remark
1	Battery cell	3.6Ah	Single
2	Casing material for single cell	Nickel plated steel	
3	Standard capacity(0.2C5A)	200Ah	
4	Rated voltage	74V	3.20V(Work voltage:3.20V)
5	Max.Charge voltage	84V	3.65V(Single Ave. charge Voltage)
6	Cut-off voltage	68V	2.50V(Single Ave. Discharge Voltage)
8	Standard charge current	20A	0.1C
9	charging Time	About 10h	
10	Max Continuous discharge current	234A	1.17C
11	Peak discharge current	420A	2.1C10seconds
12	Battery dimension	800*530*240mm	
13	(Approx.)Total weight(Approx.)	About 102kg	
14	(Max, at 1000Hz.)Impedance(Max, at 1000Hz.)	≤ 20mΩ	
15	(CC/CV) Charge method (CC/CV)	Standard	0°C~45°C
		discharge	-20°C~45°C
		storage	-20°C~45°C

Appendix 7: Charger [3]



Elcon PFC1500 Charger

[ELC1500]

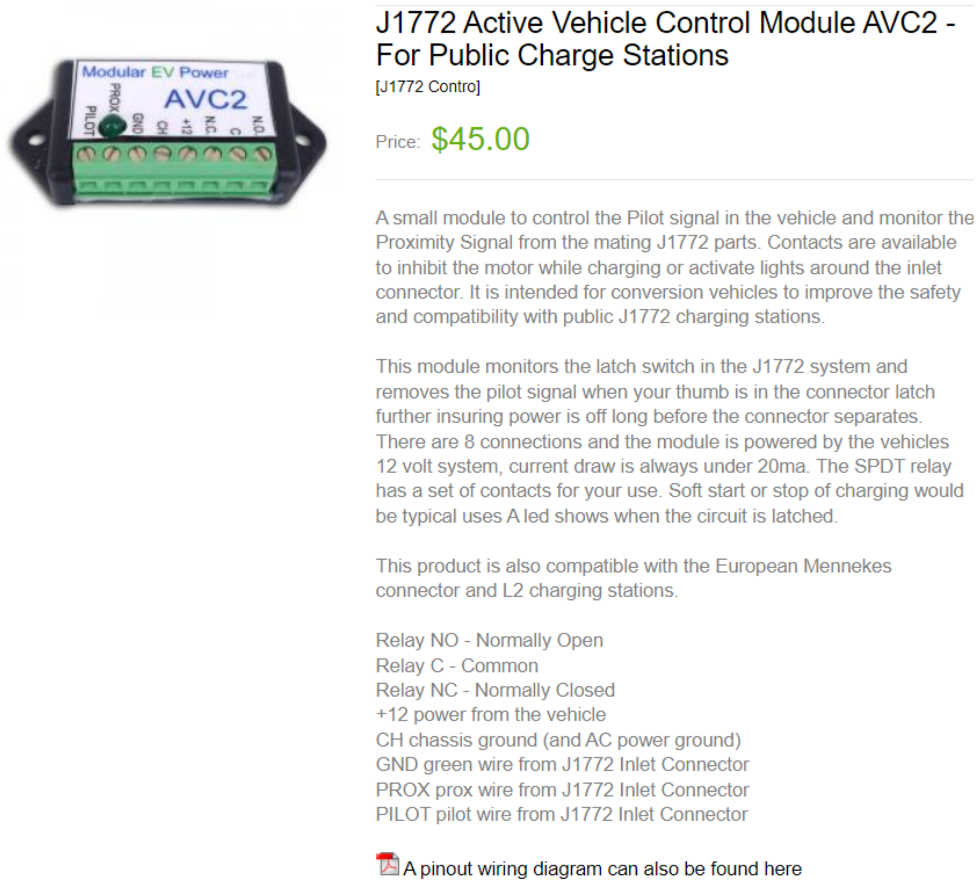
Price: $569.00

This item has been discontinued by the manufacture and is no longer available. Please contact sales@evwest.com for our replacement option.

The PFC1500 is an excellent low cost solution for low amperage charging that comes in a sealed enclosure. Being one of the more versatile chargers by being able to accept both 110v and 220v, the PFC1500 is a great low to mid range charger. These chargers are voltage specific, so we have to program the charge curves before delivery.

Input Current Range: 0.2 to 15A AC
Output Current Range: 5A to 40A DC (depending on model)
Height: 5.5 inches
Width: 6.9 inches
Length: 13.9 inches
Weight: 15.4 lbs
Mounting: 6 holes, 5/16 inch each (slotted one side)
Charge Algorithm: Programmable
Output Voltage Range: 24-320 volts (depending on model)
Input Voltage Range: 90-260 volts, 50-60 Hz
Efficiency: 92 percent
Power Factor: .98
Connection In: #12-3 Cable w/Plug
Connection Out: #12-2 Cable w/Plug
Input Protection: Internally protected
Output Protection: Internally protected
Isolated: Yes, may be combined with other chargers
Display: Tri-color LED
Preset Cutoff Voltage: Yes
Adjustable Cutoff Voltage: Yes, via factory programming
Adjustable Cutoff Time: Yes, via factory programming
Adjustable Current: Yes, via factory programming
Thermal Cutoff Point: 80Â° C reduced output, 85Â° C chutdown
Thermal Cooling: Thermostat controlled, variable speed fan
Reverse Polarity Protection: Yes
Warranty Period: One year

Appendix 8: other loading options [4] [5]



J1772 Active Vehicle Control Module AVC2 - For Public Charge Stations

[J1772 Contro]

Price: $45.00

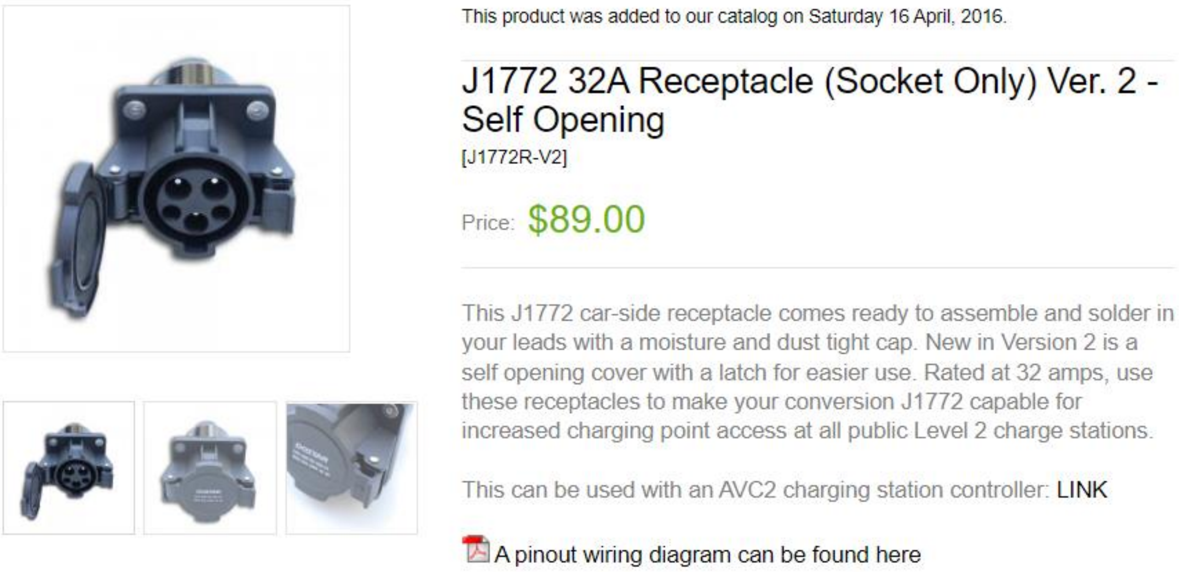
A small module to control the Pilot signal in the vehicle and monitor the Proximity Signal from the mating J1772 parts. Contacts are available to inhibit the motor while charging or activate lights around the inlet connector. It is intended for conversion vehicles to improve the safety and compatibility with public J1772 charging stations.

This module monitors the latch switch in the J1772 system and removes the pilot signal when your thumb is in the connector latch further insuring power is off long before the connector separates. There are 8 connections and the module is powered by the vehicles 12 volt system, current draw is always under 20ma. The SPDT relay has a set of contacts for your use. Soft start or stop of charging would be typical uses A led shows when the circuit is latched.

This product is also compatible with the European Mennekes connector and L2 charging stations.

Relay NO - Normally Open
Relay C - Common
Relay NC - Normally Closed
+12 power from the vehicle
CH chassis ground (and AC power ground)
GND green wire from J1772 Inlet Connector
PROX prox wire from J1772 Inlet Connector
PILOT pilot wire from J1772 Inlet Connector

A pinout wiring diagram can also be found here



This product was added to our catalog on Saturday 16 April, 2016.

J1772 32A Receptacle (Socket Only) Ver. 2 - Self Opening

[J1772R-V2]

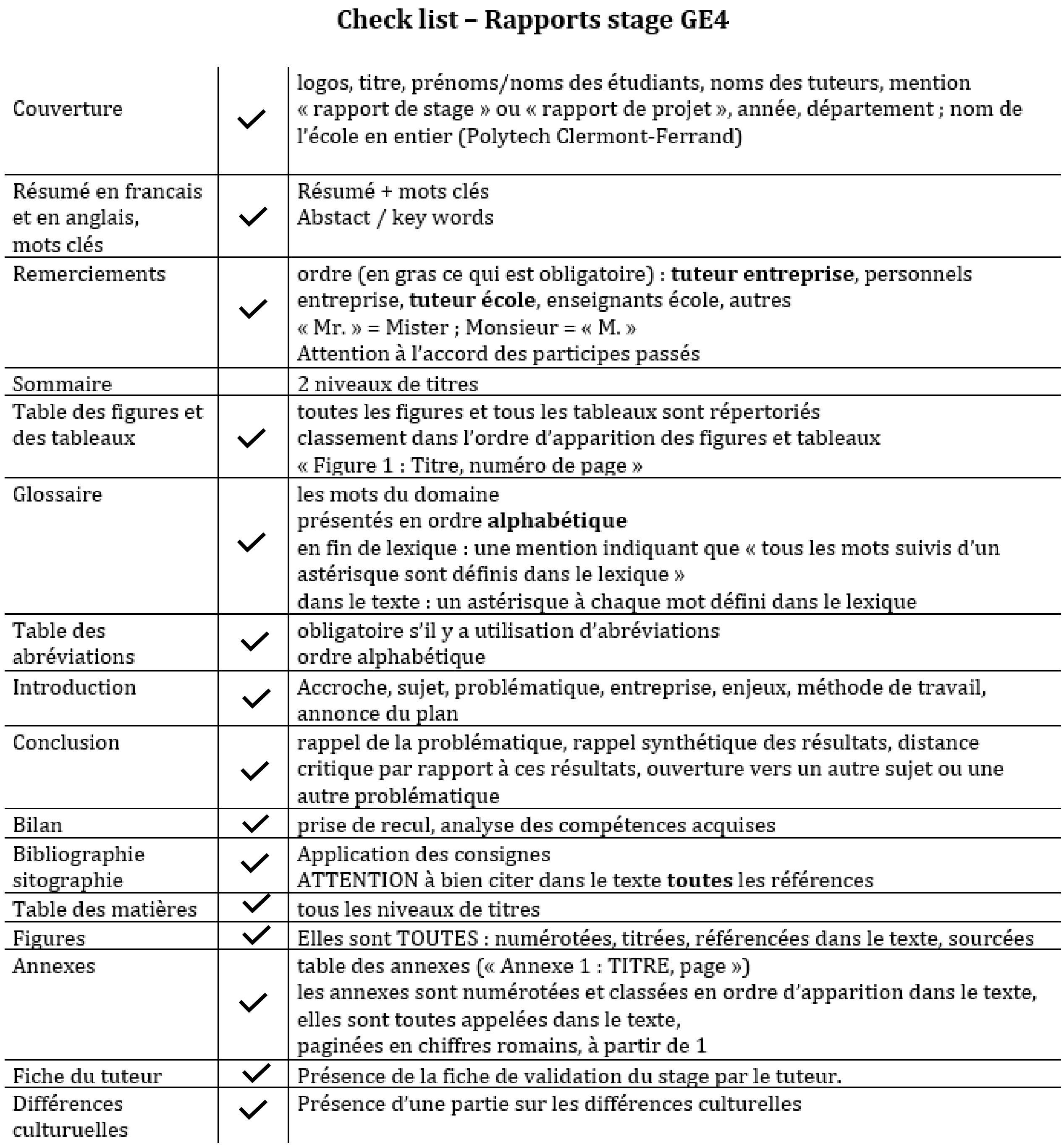
Price: $89.00

This J1772 car-side receptacle comes ready to assemble and solder in your leads with a moisture and dust tight cap. New in Version 2 is a self opening cover with a latch for easier use. Rated at 32 amps, use these receptacles to make your conversion J1772 capable for increased charging point access at all public Level 2 charge stations.

This can be used with an AVC2 charging station controller: LINK

A pinout wiring diagram can be found here

Appendix 9: Check-List



Check list – Rapports stage GE4

Couverture	✓	logos, titre, prénoms/noms des étudiants, noms des tuteurs, mention « rapport de stage » ou « rapport de projet », année, département ; nom de l'école en entier (Polytech Clermont-Ferrand)
Résumé en francais et en anglais, mots clés	✓	Résumé + mots clés Abstact / key words
Remerciements	✓	ordre (en gras ce qui est obligatoire) : **tuteur entreprise**, personnels entreprise, **tuteur école**, enseignants école, autres « Mr. » = Mister ; Monsieur = « M. » Attention à l'accord des participes passés
Sommaire		2 niveaux de titres
Table des figures et des tableaux	✓	toutes les figures et tous les tableaux sont répertoriés classement dans l'ordre d'apparition des figures et tableaux « Figure 1 : Titre, numéro de page »
Glossaire	✓	les mots du domaine présentés en ordre **alphabétique** en fin de lexique : une mention indiquant que « tous les mots suivis d'un astérisque sont définis dans le lexique » dans le texte : un astérisque à chaque mot défini dans le lexique
Table des abréviations	✓	obligatoire s'il y a utilisation d'abréviations ordre alphabétique
Introduction	✓	Accroche, sujet, problématique, entreprise, enjeux, méthode de travail, annonce du plan
Conclusion	✓	rappel de la problématique, rappel synthétique des résultats, distance critique par rapport à ces résultats, ouverture vers un autre sujet ou une autre problématique
Bilan	✓	prise de recul, analyse des compétences acquises
Bibliographie sitographie	✓	Application des consignes ATTENTION à bien citer dans le texte **toutes** les références
Table des matières	✓	tous les niveaux de titres
Figures	✓	Elles sont TOUTES : numérotées, titrées, référencées dans le texte, sourcées
Annexes	✓	table des annexes (« Annexe 1 : TITRE, page ») les annexes sont numérotées et classées en ordre d'apparition dans le texte, elles sont toutes appelées dans le texte, paginées en chiffres romains, à partir de 1
Fiche du tuteur	✓	Présence de la fiche de validation du stage par le tuteur.
Différences culturelles	✓	Présence d'une partie sur les différences culturelles

B Main scheme

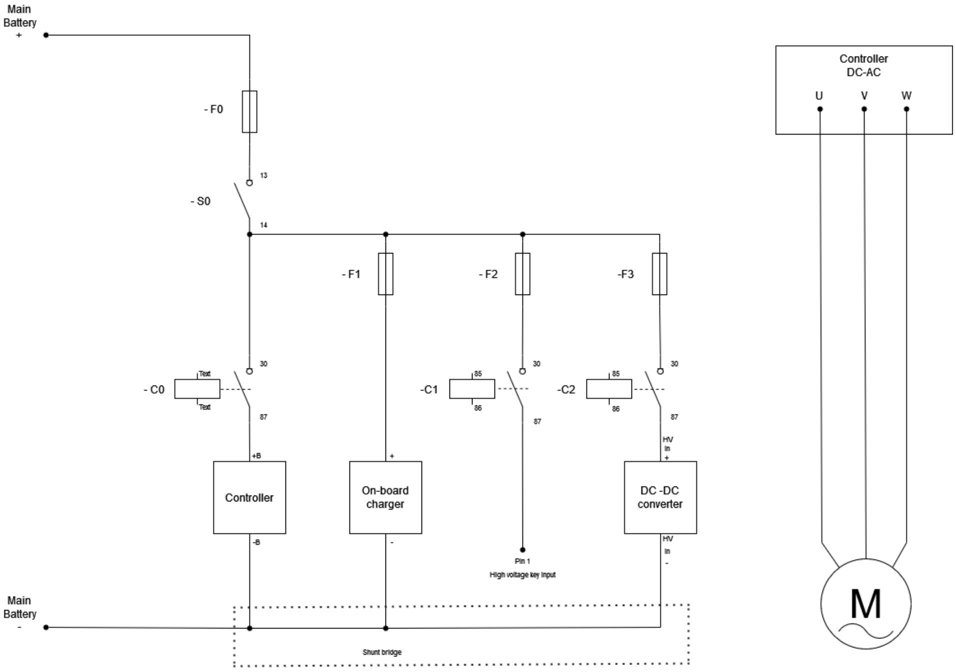


Figure B.1: Main schematic. Made in draw.io

C Throttle potentiometer datasheet

ELECTRIC VEHICLE PERFORMANCE

1788-107 La Costa Meadows
San Marcos, CA 92078
support@evwest.com
888.591.5830
evwest.com

Billet Throttle Assembly

Instructions:

1) Mount to solid chassis or ridged bracket only.

2) Adjust arm clocking (position) on shaft by removing arm retaining screw and rotating arm position and align the splines. Make sure to tighten the retention screw and apply thread lock. Check arm retention screw even if arm adjustment isn't necessary. (tighten to 30 in./lb, 3.4 Nm)

3) Adjust voltage deadband by loosening sensor retention bolts and rotating the sensor within the slots on the sensor body. Tighten sensor retention bolts, even if sensor position wasn't changed. (tighten to 30 in./lb, 3.4 Nm)

4) Install external safety return spring (user supplied). Throttle assembly contains internal spring, and shaft mounted spring, but an external return spring is *required* for safe operation.

5) Wiring. Supply the unit with 5 volt power and ground directly from the motor controller. Keep throttle wires isolated from chassis ground at all times, and do not connect to any of the vehicle's 12 volt wiring.

(1st Channel) Red: 5V Pos. - White: Variable Out - Black: 5V Neg.
(2nd Channel) Blue: 5V Pos. - Green: Variable Out - Brown: 5V Neg.

(pinout info below)

Low-Profile Precision Rotary Sensor Module

9850 Gen II Series

The 9850 Gen II Series offers a highly reliable rotary potentiometer sensor module that can be easily integrated into a wide variety of space-conscious applications requiring installation simplicity, long service life and repeatable accuracy. The 9850 Gen II Series introduces a new, lower profile (15.2mm; maximum connector receptacle height 25.9mm), designed to perform in demanding environments.

Manufactured for optimal cost-economies, the 9850 Gen II Series offers simple yet durable design strengths that can lead to significant systems costs savings. Plug-in simplicity and sealed connector contact is assured via an integral right-angle connector receptacle designed to accept industry-standard Packard Electric METRI-Pack ™ connectors. This design also eliminates weak/stress points and leaks in exposure to water.

Twelve standard models offer a choice of 180° or 120° mechanical rotation with round or slotted mounting holes for optimal installation alignment.

Electrical Specifications

Active Electrical Rotation: 85° or 130° Single Output (See Fig. 1)
85° Dual Output

Total Resistance: 5,000 ohms ±20%

Linearity: Std. ±2.0% over active electrical rotation (See Fig. 1)
(Independent) Spec. ±0.5% over active electrical rotation

Power Rating At 70°C: 0.15 Watts

Mechanical Specifications

Mechanical Rotation (Nominal): 120°-180° single; 120° dual (See Table A)

Shaft Rotation/Direction: (See Table A)

Mechanical Life: 1,000,000 full cycles
5,000,000 dither cycles

Stop Strength: 0.68 Nm max.

Torque: 0.11 Nm max.

Mounting Torque: 1.35 Nm max.

Environmental Specifications

Temperature Limits: -40°C to +125°C

Vibration: 15 Gs, 50 to 1,000 Hz

Humidity: 95% @ 40°C

Shock: 50 Gs max.

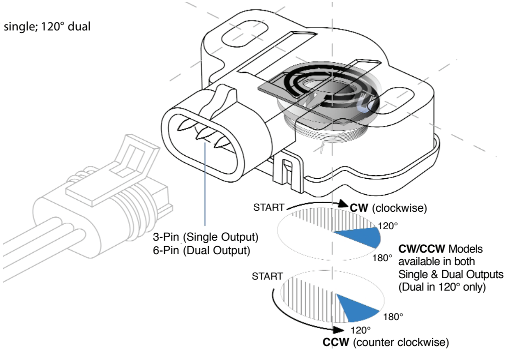
Options Available:

Integrated switch functions, user-specific electrical/mechanical rotation, mounting hole inserts, resistance and linearities.

Generation II Benefits:

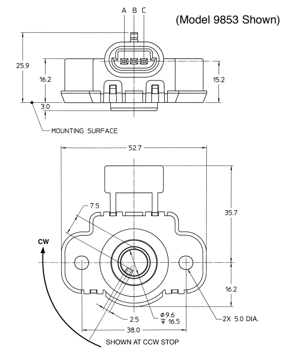
- Dual-output offers the added functionality of two sensors in a single sensor
- Sealed integral interface accepts industry-standard Packard Electric METRI-Pack ™ connectors
- Low-profile design answers space-conscious applications
- Additional mechanical rotation angles available

Integrates Duncan's Proprietary Thick Film Element & Precious Metal Contact Technology with Maximum Packaging Flexibility



Models 9851-9858 – Single Output (3-Pin)

(Model 9853 Shown)



Models 9861-9864 – Dual Output (6-Pin)

(Model 9862 Shown)

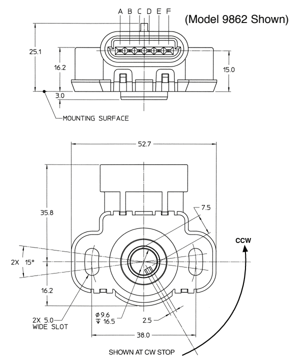
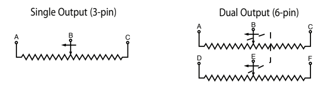


Table A

Model	Mechanical Rotation	Active Electrical Rotation	Rotation* Direction	Mounting Hole[1]
9851	120°	85°	CW	S
9852	120°	85°	CCW	S
9853	120°	85°	CW	R
9854	120°	85°	CCW	R
9855	180°	130°	CW	S
9856	180°	130°	CCW	S
9857	180°	130°	CW	R
9858	180°	130°	CCW	R

Model	Mechanical Rotation	Active Electrical Rotation	Rotation* Direction	Mounting Hole[1]
9861	120°	85°	CW	S
9862	120°	85°	CCW	S
9863	120°	85°	CW	R
9864	120°	85°	CCW	R



*Spring-Return: CW Sensors return contact to CCW end
CCW Sensors return contact to CW end

[1] Mounting Hole style: S = Slotted, R = Round

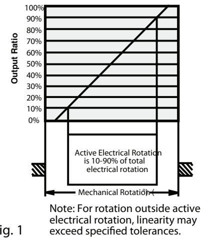


Fig. 1

Note: For rotation outside active electrical rotation, linearity may exceed specified tolerances.

Mating Connector/Interface Information:

Sensor mates with Packard Electric METRI-Pack ™ Series 150 Connectors

Ordering Information

98XX	R5K	L2.0
Model No. (See Table A)	Standard Resistance	Standard Linearity (%)

Example: 9855 R5K L2.0 specifies a model 9855 (180° mechanical rotation, CW rotation direction) single output, 3-Pin Sensor Module with slotted mounting holes, standard resistance 5K ohms ±20%, Linearity ±2%.

Made in the USA

D Curtis 1238e Controller Manual

CURTIS

Manual

Models **1232E / 34E / 36E / 38E** and **1232SE / 34SE / 36SE / 38SE**

Enhanced AC Controllers for Induction Motors and Surface Permanent Magnet Motors

» Software Version OS 31.0 «

Curtis Instruments, Inc.
200 Kisco Avenue
Mt. Kisco, NY 10549
www.curtisinstruments.com

⚠ Read Instructions Carefully!

53096, OS31 May 2017

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The Curtis Difference
You feel it when you drive it

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FIGURES

1— INTRODUCTION

Curtis 1232E/SE, 1234E/SE, 1236E/SE, and 1238E/SE AC motor controllers provide accurate, dependable, and highly efficient control of speed and torque of AC induction motors (ACIM) and surface permanent magnet synchronous motors (SPM).

These AC controllers contain two microprocessors to provide exceptional capability and functional safety. The primary microprocessor runs an advanced field-oriented AC motor control while simultaneously running VCL software in an embedded logic controller. The second microprocessor continuously monitors the operation of the system, redundantly measuring inputs, crosschecking results, and verifying critical timing and operations.

VCL (Vehicle Control Language) is an innovative software programming language developed by Curtis. Many electric vehicle functions are uniquely built into the VCL code, and additional functions can be created by OEMs as required. VCL opens new avenues of customization, allowing specific vehicle application functions to be created quickly and easily within the motor controller itself, often eliminating the need to use separate vehicle manager modules.

The CANbus communications included within these controllers allow these AC motor controllers to function as system CAN masters (Server) or CAN slaves (Client) as part of an efficient distributed system. Inputs and outputs can be optimally shared throughout the system, minimizing wiring and creating integrated functions that often reduce the cost of the system.

These controllers are the ideal solution for traction, hoist, dual drive, and other motor drive and vehicle control needs.

Figure 1

Curtis AC induction and surface permanent magnet motor controllers:
from left to right, models 1232SE, 1234E, 1236E, and 1238E.
The E and SE models look similar, and share the same standard features.

Like all Curtis controllers, the E and SE models offer superior operator control of motor drive performance. Features include:

- Closed-loop speed and torque control for both induction (ACIM) and surface permanent magnet (SPM) motors.
- High efficiency, field-oriented motor control algorithms that enable maximum possible motor torque generation for all operating conditions.
- Advanced Pulse Width Modulation technology for efficient use of battery voltage, low motor harmonics, low torque ripple, and minimized switching losses.
- Extremely wide torque/speed range including full regeneration capability.
- Full field-weakening capability with ACIM motors; full control up to no-load base speed with SPM motors.
- Smooth low speed control, including zero speed.
- Adaptation of control algorithm to motor temperature variation for optimal performance and reduced motor heating.
- Power limiting maps allow performance customization for reduced motor heating and consistent performance over varying battery state-of-charge.
- Thermal cutback, warning, and automatic shutdown provide protection to motor and controller.
- Insulated metal substrate power base provides superior heat transfer for increased reliability.
- Built-in auto-characterization routines for effective in-vehicle optimization of motor performance and efficiency.
- Powerful operating system allows parallel processing of vehicle control tasks, motor control tasks, and user configurable programmable logic (VCL).
- A wide range of I/O can be applied wherever needed, for maximum distributed system control.
- Built-in Dual Drive software allows easy setup and control of typical dual-drive vehicles, without VCL.
- Internal battery-state-of-charge, hourmeter, and maintenance timers.
- CANopen compatible CANbus connection; other CANbus protocols are configurable through VCL.
- Significantly increased CAN master capabilities, VCL execution speed, and VCL code space
- Field-programmable, with flash downloadable main operating code.
- Easily programmable through the Curtis 1313 handheld programmer and 1314 PC Programming Station.
- Rugged sealed housing and connectors meet IP65 environmental sealing standards for use in harsh environments.
- Compliance with Machinery Directives 2006/42/EC and EN13849-1.

Getting the most out of your Curtis controller

Read and apply the information in this manual. The Installation/Wiring, Initial Setup, and Tuning Guide chapters are critical to proper operation of your controller. For technical support, contact the Curtis distributor where you obtained your controller or the Curtis sales-support office in your region.

2 — INSTALLATION AND WIRING

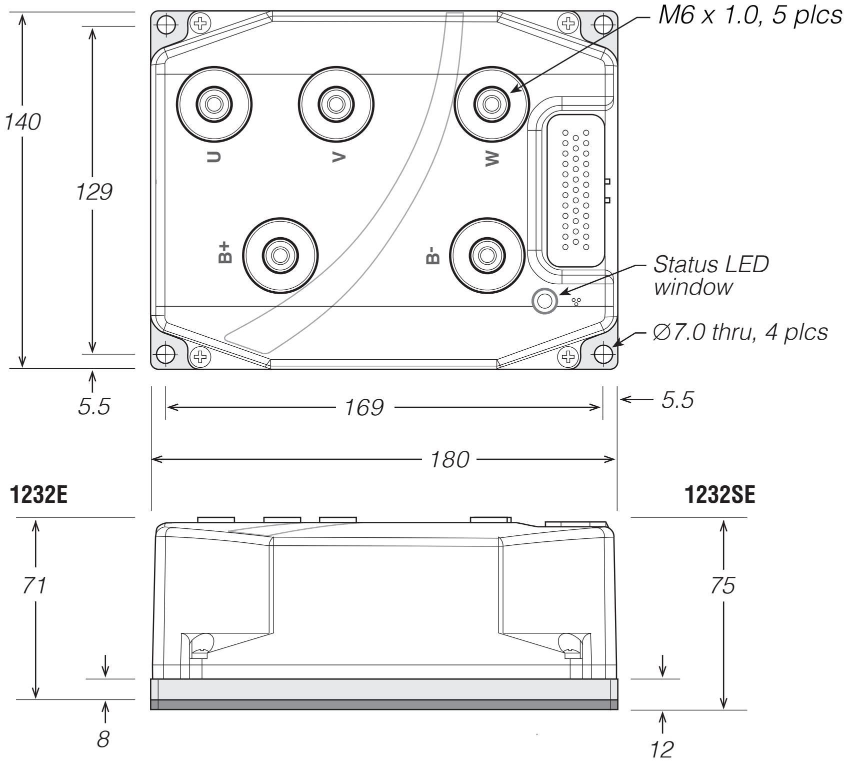
MOUNTING THE CONTROLLER

The outline and mounting hole dimensions for the 1232E/SE controller are shown in Figure 2a, for the 1234E/SE controller in Figure 2b, and for the 1236E/SE and 1238E/SE controllers in Figure 2c. When an Ampseal plug housing is mated with the 35-pin logic receptacle, these controllers meet the IP65 requirements for environmental protection against dust and water. Nevertheless, in order to prevent external corrosion and leakage paths from developing, **the mounting location should be carefully chosen to keep the controller as clean and dry as possible.**

Mount the controller to a flat surface devoid of protrusions, ridges, or a curvature that can cause damage or distortion to its heatsink (the base plate). Secure the controller using four 6 mm (1/4") diameter bolts evenly torqued to the vehicle's mounting surface. These controller's heatsink (bottom surface) have a typical roughness grade of N8 (ISO 1302), with a flatness tolerance of < 5 mm (0.13 per 25 mm). A thermal joint compound is recommended to improve heat conduction from the controller heatsink to the vehicle's mounting surface. Typically, when properly mounted to a larger metal surface, additional heat-sinking or fan-cooling is not necessary to meet the application's peak and continuous current ratings.

Figure 2a

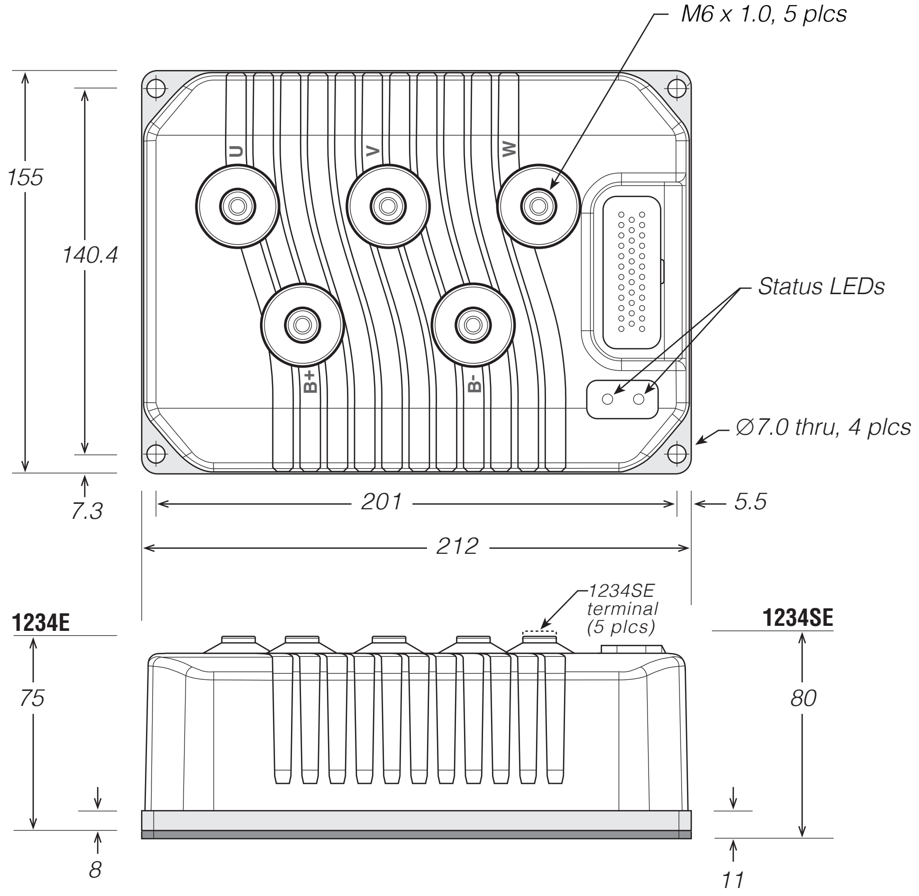
Mounting dimensions, Curtis 1232E and 1232SE motor controllers.



Note: The SE has a thicker base.
Dimensions in millimeters.

Figure 2b

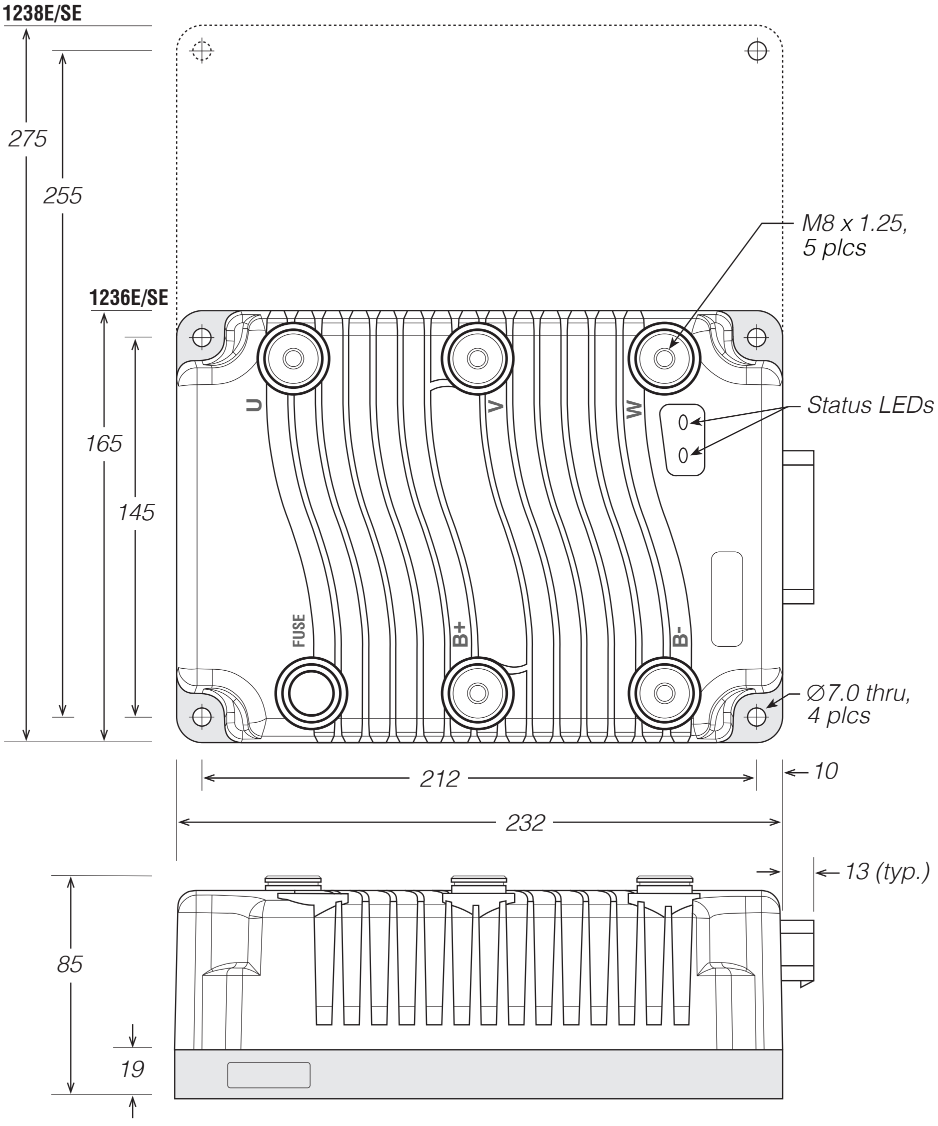
Mounting dimensions, Curtis 1234E and 1234SE motor controllers.



Note: The SE has a thicker base and taller terminals.
Dimensions in millimeters.

Figure 2c

Mounting dimensions, Curtis 1236E/SE and 1238E/SE motor controllers.



Dimensions in millimeters.

⚠ WARNING

Working on electrical systems is potentially dangerous. Protect yourself against uncontrolled operation, high current arcs, and outgassing from lead-acid batteries:

UNCONTROLLED OPERATION — Some conditions could cause the motor to run out of control. Disconnect the motor or jack up the vehicle and get the drive wheels off the ground before attempting any work on the motor control circuitry.

HIGH CURRENT ARCS — Batteries can supply very high power, and arcing can occur if they are short circuited. Always open the battery circuit before working on the motor control circuit. Wear safety glasses, and use properly insulated tools to prevent shorts.

LEAD-ACID BATTERIES — Charging or discharging generates hydrogen gas, which can build up in and around the batteries. Follow the battery manufacturer's safety recommendations. Wear safety glasses.

You will need to take steps during the design and development of your end product to ensure that its EMC performance complies with applicable regulations; suggestions are presented in Appendix A.

These controllers contain **ESD-sensitive components**. Use appropriate precautions in connecting, disconnecting, and handling the controller. See installation suggestions in Appendix A for protecting the controller from ESD damage.

HIGH POWER CONNECTIONS

There are five high power terminals, identified on the controller housing as **B+**, **B–**, **U**, **V**, and **W**.

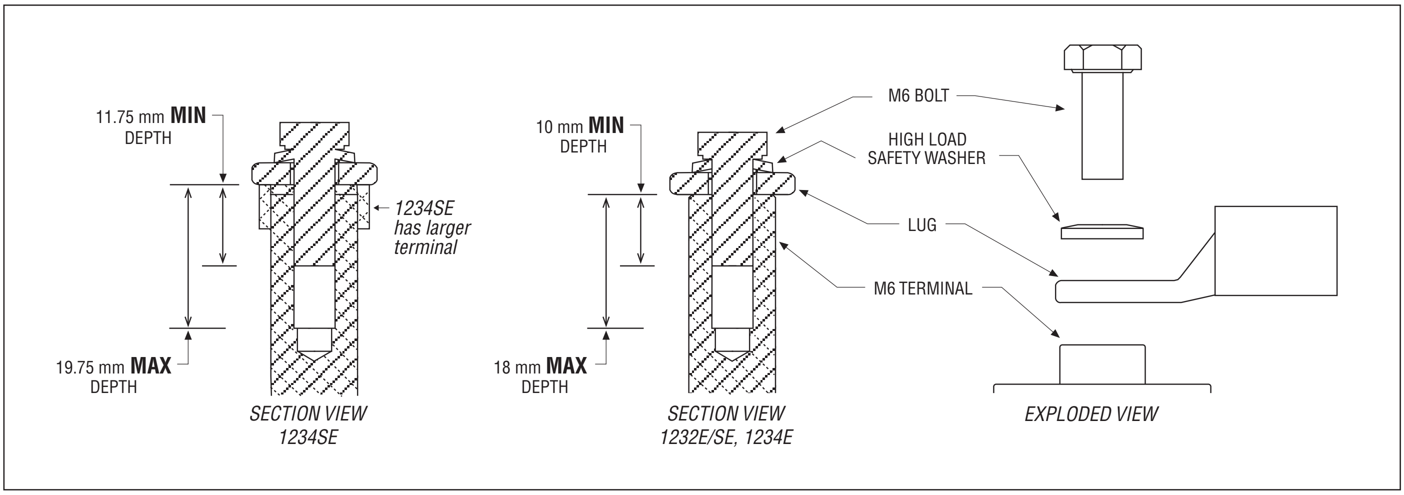
Table 1 High Powered Connections

Terminal	Function
B+	Positive battery to controller
B–	Negative battery to controller
U	Motor phase U
V	Motor phase V
W	Motor phase W

Lug Assembly: 1232E/SE and 1234E/SE models

Five aluminum M6 terminals are provided. Lugs should be installed as follows, using M6 bolts sized to provide proper engagement (see diagram):

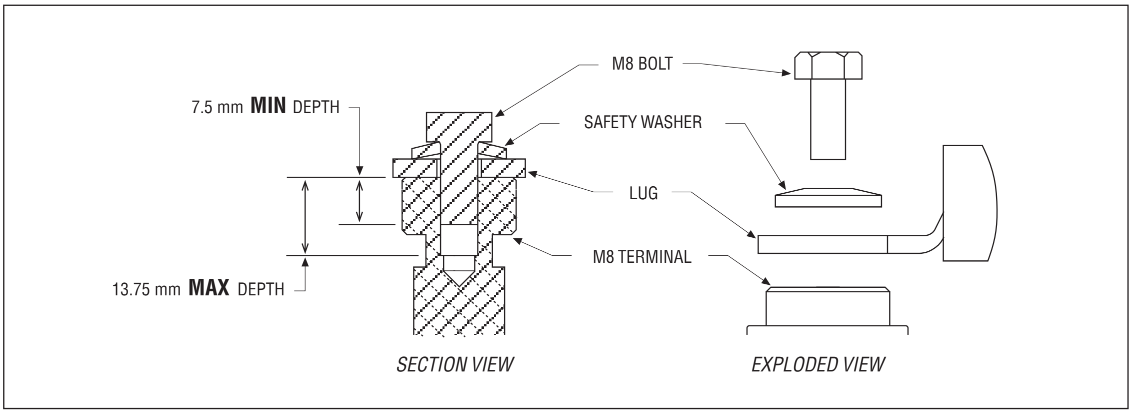
- Place the lug on top of the aluminum terminal, followed by a high-load safety washer with its convex side on top. The washer should be a SCHNORR 416320, or equivalent.
- If two lugs are used on the same terminal, stack them so the lug carrying the least current is on top.
- Tighten the assembly to 10.2 ±1.1 N·m (90 ±10 in-lbs).



Lug assembly: 1236E/SE and 1238E/SE models

Five M8 terminals are provided. Lugs should be installed as follows, using M8 bolts sized to provide proper engagement (see diagram):

- Place the lug on top of the terminal, followed by a safety washer with its convex side on top. The washer should be a SCHNORR 700800, or equivalent.
- If two lugs are used on the same terminal, stack them so the lug carrying the least current is on top.
- Tighten the assembly to 9.6 ±0.9 N·m (85 ±8 in-lbs).



High Power Wiring Guidelines: All Models

Battery cables (B+, B–)

These two cables should be run close to each other between the controller and the battery. Use high quality copper lugs and observe the recommended torque ratings. For best noise immunity the cables should not run across the center section of the controller. With multiple high current controllers, use a star ground from the battery **B–** terminal.

Motor wiring (U, V, W)

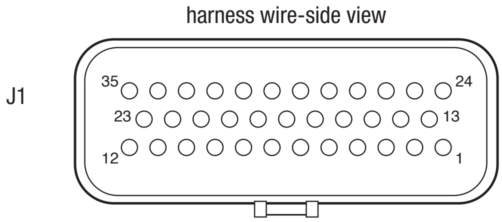
The three phase wires should be close to the same length and bundled together as they run between the controller and the motor. The cable lengths should be kept as short as possible. Use high quality copper lugs and observe the recommended torque ratings.

For optimum noise immunity, the motor cables should not run across the center section of the controller. In applications that seek the lowest possible emissions, a shield can be placed around the bundled motor cables and connected to the B– terminal at the controller. Typical installations will readily pass the emissions standards without a shield. Low current signal wires should not be run parallel to the motor cables. When necessary they should cross the motor cables at a right angle to minimize noise coupling. Refer to Appendix A for further information about Electromagnetic Compatibility (EMC).

LOW POWER 35-PIN CONNECTIONS

All low power connections are made through a single 35-pin AMPSEAL connector. The mating plug housing is AMP p/n 776164-1 and the gold-plated socket terminals are AMP p/n 770520 (Strip form) and 770854-3 (loose piece). The connector will accept 0.5 – 1.25 mm (20 – 16 AWG) wire with a 1.7 – 2.7 mm diameter (thin-wall insulation). Seal any non-used connector positions that have the silo-diaphragm pierced with seal plug 770678-1.

The 35 individual pins are characterized in Table 2.



Low Power Wiring Guidelines

Position feedback (Pins 7, 26, 31, 32)

All four wires (+5V, Feedback A, Feedback B, and I/O ground) should be bundled together as they run between the motor and controller logic connector. These can often be run with the rest of the low current wiring harness. The encoder cables should not be run near the motor cables. In applications where this is necessary, shielded cable should be used with the ground shield connected to the I/O ground (pin 7) at only the controller side. In extreme applications, common mode filters (e.g. ferrite beads) could be used.

CANbus (Pins 21, 23, 34, 35)

It is recommended that the CAN wires be run as a twisted pair. However, many successful applications at 125 kbit/s are run without twisting, simply using two lines bundled in with the rest of the low current wiring. The CANbus wiring should be kept away from the high current cables and cross them at right angles when necessary.

All other low power wiring

The remaining low power wiring should be run according to standard practices. When designing the vehicle's wiring and routing, keep the input lines such as throttle, brake, temperature, and the above mentioned encoder or Sin/Cos sensor signals separate from controller's output lines such as the coil driver outputs. Avoid routing the low-power wiring parallel to the high power (and current) battery and motor cables.

Table 2 Low Power Connections

Pin	Name	Description	Related VCL*	
			Function	References
1	KSI	Keyswitch input. Provides logic power for the controller and power for the coil drivers.		Keyswitch_Voltage
2	Prop. Driver	Proportional driver. This is a coil driver with current control capability typically used for a proportional valve on a hydraulic manifold. Can also be used as a digital input.	Automate_PWM() Put_PWM() Automate_Frequency_Output() Frequency_Output_Duty_Cycle()	Sw_13 PWM5 PD_Current PD_Output PD_Throttle VCL_PD_Throttle
3	Driver 4	Generic driver #4; can also be used as a digital input. Has low frequency PWM capabilities.	Automate_PWM() Put_PWM()	Sw_12 PWM4 PWM4_Output
4	Driver 3	Generic driver #3; can also be used as a digital input. Has low frequency PWM capabilities. Typically used for pump contactor.	Automate_PWM() Put_PWM()	Sw_11 PWM3 PWM3_Output
5	Driver 2	Generic driver #2; can also be used as a digital input. Has low frequency PWM capabilities and a slightly higher current rating. Typically used for electromagnetic brake.	Automate_PWM() Put_PWM()	Sw_10 PWM2 PWM2_Output
6	Driver 1	Generic driver #1; can also be used as a digital input. Has low frequency PWM capabilities. Typically used for main contactor.	Automate_PWM() Put_PWM() Set-Interlock() Clear_Interlock()	Sw_9 PWM1 PWM1_Output Interlock_State Main_State
7	I/O Ground	Input and output ground reference.		
8	Switch 2 Analog 2	Can be used as generic switch input #2 or as generic analog input #2. Typically used as the motor temperature analog input.		Sw_2 Analog2_Input Motor_Temperature
9	Switch 3	Generic switch input #3. Typically used as the interlock switch.		Sw_3
10	Switch 4	Generic switch input #4.		Sw_4
11	Switch 5	Generic switch input #5.		Sw_5
12	Switch 6	Generic switch input #6.		Sw_6
13	Coil Return	This is the coil return pin (at B+ potential) for all the contactor coils.		
14	Switch 16	Generic switch input #16.		Sw_16
15	Throttle Pot High	Pot high connection for a 3-wire throttle pot.		
16	Throttle Pot Wiper	Pot wiper connection for the throttle pot.	Setup_Pot() Setup_Pot_Faults()	Throttle_Pot Throttle_Pot_Output
17	Pot2 Wiper	Pot wiper connection for the brake pot.	Setup_Pot() Setup_Pot_Faults()	Brake_Pot Brake_Pot_Output

** The related VCL columns are vital when writing VCL code (see Chapter 10). VCL "functions" are used to access the various I/Os; VCL "references" are predefined names for specific pins. Refer to the OS SysInfo file for specific VCL functions, controller system variables, usage, and CAN Object IDs.*

Table 2 Low Power Connections, cont'd

Pin	Name	Description	Related VCL*	
			Function	References
18	Pot Low	Common pot low connection for the throttle and brake pots.		Pot_Low_Output
19	Digital Out 6	An On/Off output driver. Can also be used as a digital input.	Set_DigOut() Clear_DigOut()	Sw_14 DigOut6 Dig6_Output
20	Digital Out 7	An On/Off output driver. Can also be used as a digital input.	Set_DigOut() Clear_DigOut()	Sw_15 DigOut7 Dig7_Output
21	CAN Term H	High connection for the CAN termination jumper.		
22	Switch 7	Generic switch input #7. Typically used as the Forward switch.		Sw_7
23	CAN H	CANbus high.	Setup_CAN() Setup_Mailbox() Send_Mailbox() etc.	
24	Switch 1 Analog 1	Can be used as generic switch input #1 or as generic analog input #1. Typically used for emergency reverse switch (if applicable).		Sw_1 Analog1_Input
25	+12V Out	Unregulated low power +12V output.		Ext_Supply_Current
26	+5V Out	Regulated low power +5V output.		5_Volts_Output Ext_Supply_Current
27	Pot2 High	Pot high connection for a 3-wire brake pot.		
28	Serial TX	Serial transmit line for display or flash update.	Setup_Serial()	
29	Serial RX	Serial receive line for flash update	Setup_Serial()	
30	Analog Output**	Low power, low frequency 0 V to 10 V analog output.	Automate_PWM() Put_PWM()	PWM6 Analog_Output
31	Position Feedback A	Quadrature encoder input phase A (ACIM motors). Sin/Cos sensor input sine (SPM motors).		Motor_RPM MotorspeedA Encoder_Sin_Input_Compensated
32	Position Feedback B	Quadrature encoder input phase B (ACIM motors). Sin/Cos sensor input sine (SPM motors).		Motor_RPM MotorspeedB Encoder_Cos_Input_Compensated
33	Switch 8	Generic switch input #8. Typically used as the Reverse switch.		Sw_8
34	CAN Term L	Low connection for the CANbus termination jumper.		
35	CAN L	CANbus low.	Setup_CAN() Setup_Mailbox() Send_Mailbox() etc.	

** The related VCL columns are vital when writing VCL code (see Chapter 10). VCL "functions" are used to access the various I/Os; VCL "references" are predefined names for specific pins. Refer to the OS SysInfo file for specific VCL functions, controller system variables, usage, and CAN Object IDs.*

** * Pin 30 not connected on 1232E/SE controllers.*

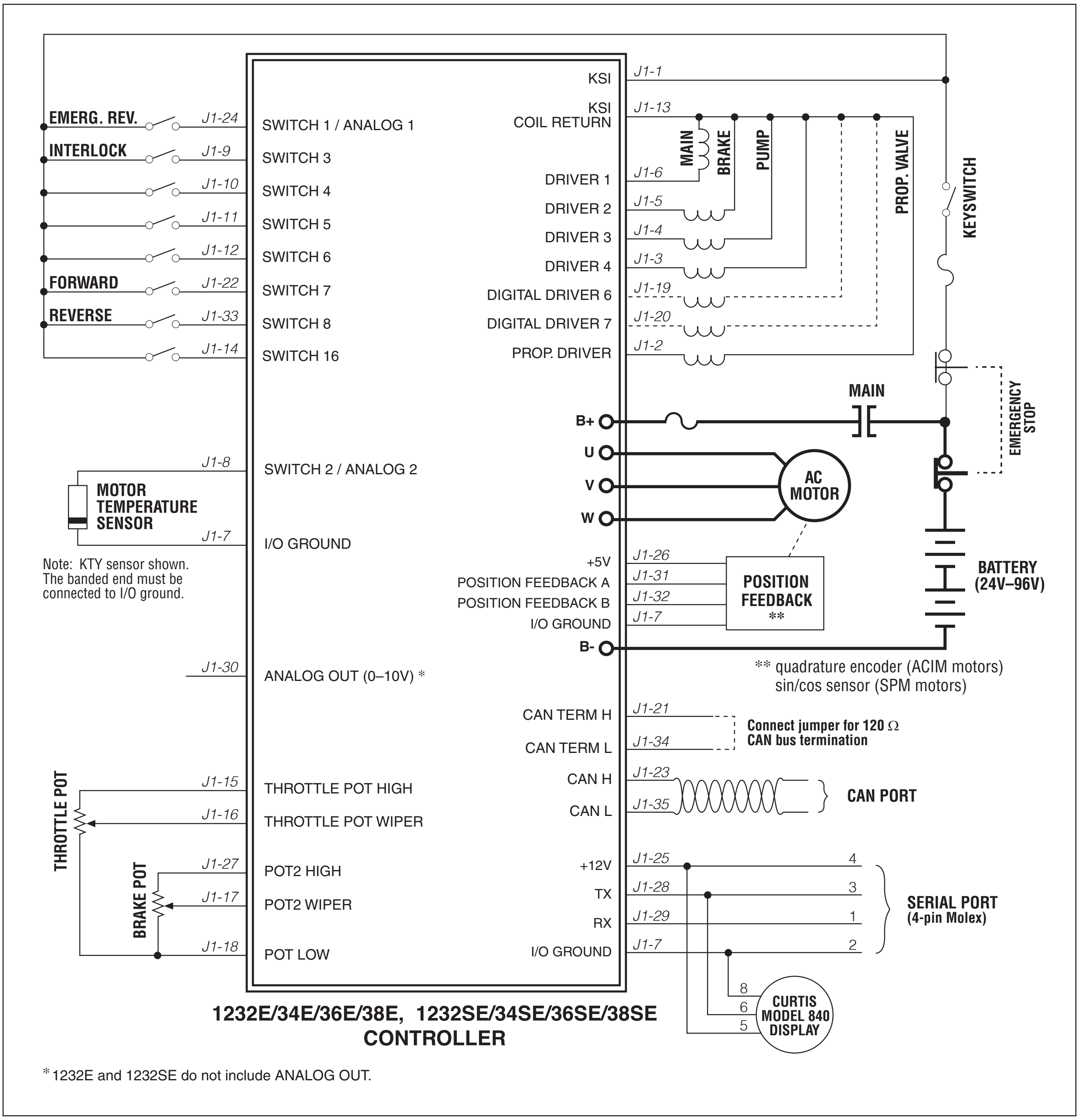
CONTROLLER WIRING: BASIC CONFIGURATION

A basic wiring diagram is shown in Figure 3. Throttle and brake are shown in the diagram as 3-wire potentiometers; other types of throttle and brake inputs are easily accommodated, and are discussed in the following throttle wiring section.

The main contactor coil must be wired directly to the controller as shown in Figure 3 to meet EEC safety requirements. The controller can be programmed to check for welded or missing contactor faults and uses the main contactor coil driver output to remove power from the controller and motor

Figure 3

Basic wiring diagram, Curtis 1232E/SE, 34E/SE, 36E/SE, and 38E/SE motor controllers.



* 1232E and 1232SE do not include ANALOG OUT.

in the event of various other faults. **If the main contactor coil is not wired to Pin 6 of the 35-pin connector as shown, the controller will not be able to open the main contactor in serious fault conditions and the system will therefore not meet EEC safety requirements.**

Note that the basic wiring diagram is designed for generic applications and may not fully meet the requirements of your system. These controllers have very flexible I/O and wiring configurations; you may wish to contact your Curtis distributor or support engineer to discuss your particular application.

SWITCH INPUT WIRING

The following inputs are dedicated to specific functions when the parameter settings are as shown:

Switch 1: Emergency Reverse input if the EMR Enable = On and EMR Type = 0 or 2 (see page 65).

Switch 3: Interlock input if Interlock Type = 0 (see page 52).

Switch 5: Lift input (depends on VCL program).

Switch 6: Lower input (depends on VCL program).

Switch 7: Forward input if Throttle Type = 1–3 (see page 46).

Switch 8: Reverse input if Throttle Type = 1–3 (see page 46).

LOW POWER CIRCUIT SPECIFICATIONS

The input/output circuits wired to the 35-pin connector can be grouped by type as follows; their electrical characteristics are discussed below.

- Digital Inputs
- Digital and PWM Outputs
- Analog Inputs
- Analog Output
- Power Supply Outputs
- KSI and Coil Return Inputs
- Throttle and Brake Inputs
- Communications Ports I/O
- Position Feedback Inputs

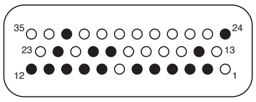
Digital Inputs

These control lines can be used as digital (on/off) inputs. Normal “on” connection is direct to B+; “off” is direct to B–. Input will pull low (off) if no connection is made. All digital inputs are protected against shorts to B+ or B–.

Nine of these lines (Switches 1–8, 16) are designed to pull current to keep switch contacts clean and prevent leakage paths from causing false signals.

The remaining lines are digital inputs associated with driver outputs; note that they have much higher input impedances. The two digital output lines, Digital Out 6 and 7, can also be read as inputs, and are therefore included in this group.

The digital inputs at pins 24 and 8 can also be used as analog inputs, and are included in that group as well.



Quick Links:
Figure 3 wiring diagram p.12

DIGITAL INPUT SPECIFICATIONS

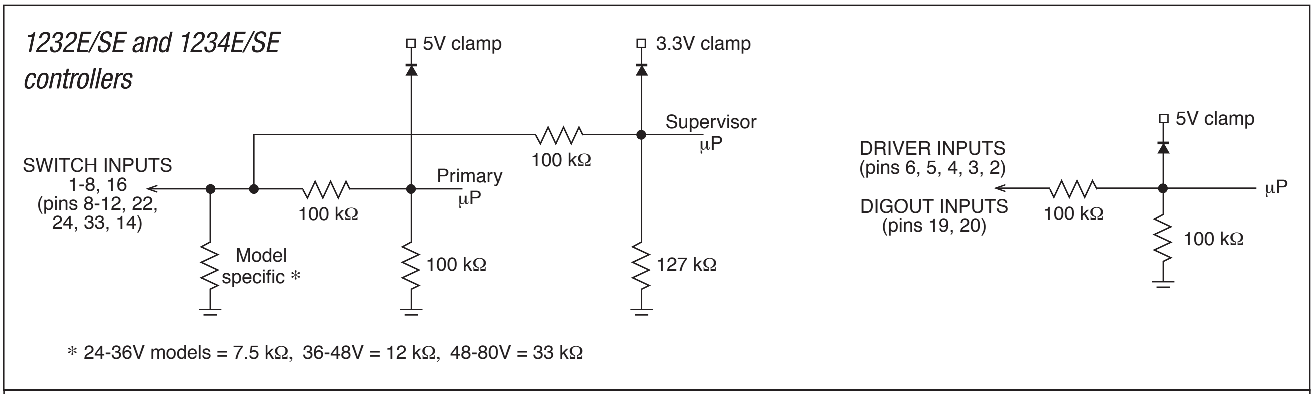
Name	Pin	Logic Thresholds	Input impedance*	Voltage range†	ESD Tolerance
Switch 1	24	Rising edge= 4.4V max Falling edge= 1.5V min	*24-36V models:* 7.0 kΩ, 7.2 kΩ *36-48V models:* 10.8 kΩ, 11.2 kΩ *48-80V models:* 25.2 kΩ, 27.3 kΩ *72-96V models:* n/a, 29.4 kΩ	−10V to (MaxV + 10 V)	± 8 kV (direct strike)
Switch 2	8				
Switch 3	9				
Switch 4	10				
Switch 5	11				
Switch 6	12				
Switch 7	22				
Switch 8	33				
Switch 16	14				
Digital Out 6	19		150 kΩ to 300 kΩ	−5V to (MaxV + 10 V)	
Digital Out 7	20				
Driver 1	6				
Driver 2	5				
Driver 3	4				
Driver 4	3				
Prop Driver	2				

**The first value is for 1232E/SE and 1234E/SE controllers, and the second value is for 1236E/SE and 1238E/SE controllers.*

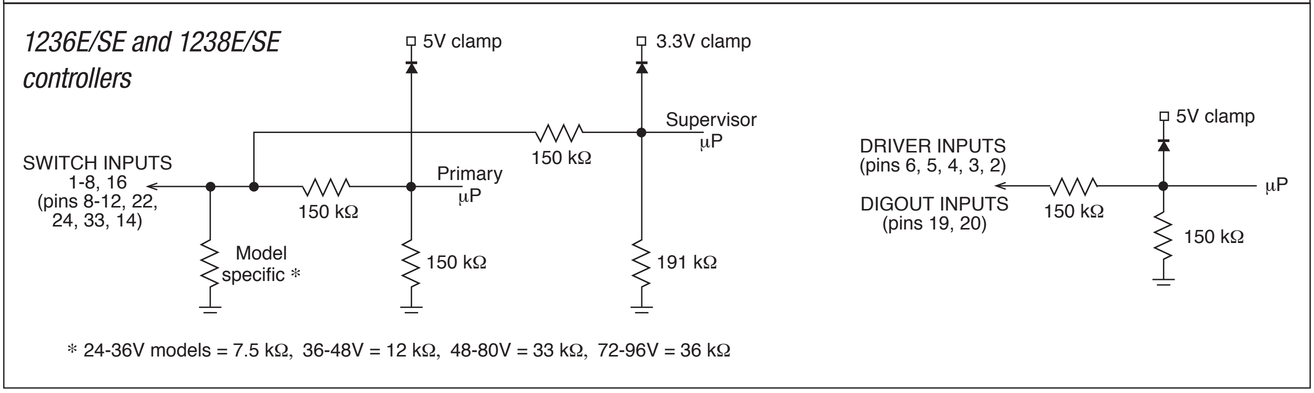
† "MaxV" in this and the following tables is the controller's maximum voltage; see Table D-1 for the maximum voltage of each model.

NOTE: *The voltage at the switch inputs 3–8 and 16 must be above the high threshold or below the low threshold for proper operation. Allowing these inputs to fall between these thresholds for more than 100 milliseconds could result in a Supervisor Fault (fault code 77).*

DIGITAL INPUT IMPEDANCE CIRCUITS


1232E/SE and 1234E/SE controllers

* 24-36V models = 7.5 kΩ, 36-48V = 12 kΩ, 48-80V = 33 kΩ


1236E/SE and 1238E/SE controllers

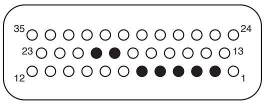
* 24-36V models = 7.5 kΩ, 36-48V = 12 kΩ, 48-80V = 33 kΩ, 72-96V = 36 kΩ

Digital and PWM Outputs

Seven digital (on/off) and PWM output drivers are available. One of these, the proportional driver, can be operated in a current control mode for driving a proportional valve or similar load. The frequency of this driver is normally 18 kHz, but this output can also serve to drive an electronic speedometer or tachometer using the VCL function Automate_Frequency_Output(); see page 125.

Each output can be independently turned on continuously (low level) or pulse width modulated to set the average output voltage. These outputs are intended to drive inductive loads such as contactors and electromagnetic brakes but could also be used to drive resistive loads if peak current ratings are not exceeded. All these outputs are protected against shorts to B+ or B–. All inductive loads should be connected to the coil return (pin 13), which provides flyback diode protection.

These lines can also be used as digital inputs, and are included in that group as well.



DIGITAL and PWM OUTPUT SPECIFICATIONS

Name	Pin	PWM	PV Current	Frequency	Output Current	Protected Voltage	ESD Tolerance
Driver 1	6	0 to 100% Duty Cycle	N/A	120 to 1000 Hz *	2A Max	−0.5 V to (MaxV + 10 V)	± 8 kV (direct strike)
Driver 2	5				3A Max		
Driver 3	4				2A Max		
Driver 4	3						
Prop Driver	2		0 to 2A in 607 nominal steps	18 kHz			
Digital Out 6	19	On / Off	N/A	N/A	1A Max		
Digital Out 7	20						

**Drivers 1–4 Fequency is set by the PWM Frequency parameter.*

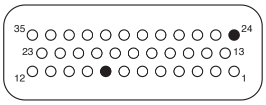
Analog Inputs

Quick Links:
Figure 3 wiring diagram p.12
Motor Temp Sensor p.61

Two control lines can be used as analog inputs. Both inputs are protected against shorts to B+ or B–.

Typically Analog 2 is used as the input for the motor temperature sensor. This input provides a constant current appropriate for a thermistor sensor. Some standard predefined motor temperature sensors are supported in software (see the motor's Sensor Type parameter). Note: The industry standard KTY temperature sensors are silicon temperature sensors with a polarity band; the polarity band of a KTY sensor must be the end connected to I/O Ground (pin 7).

These lines can also be used as digital inputs, and are included in that group as well (see page 13).



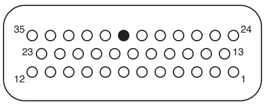
ANALOG INPUT SPECIFICATIONS

Signal Name	Pin	Operating Voltage	Input impedance*	Protected Voltage	ESD Tolerance
Analog 1	24	0 to 10V in 1024 steps	*24-36 V models:* 6.9 kΩ, 7.1 kΩ *36-48 V models:* 10.5 kΩ, 11.0 kΩ *48-80 V models:* 23.8 kΩ, 28.1 kΩ *72-96 V models:* n/a, 28.1 kΩ	−10 V to (MaxV + 10 V)	± 8 kV (direct strike)
Analog 2	8				

** The first value is for 1232E/SE and 1234E/SE controllers, and the second value is for 1236E/SE and 1238E/SE controllers.*

Analog Outputs

A single line is available as a low power analog output and is intended to drive instrumentation such as a battery discharge indicator. This output is generated from a filtered PWM signal and has about 1% ripple. The 2% settling time is <25 ms for a 0–5 V step and <30 ms for a 0–10 V step. This output line is protected against shorts to B+ or B–. Note: The 1232E/SE does not have this analog output.



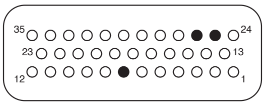
ANALOG OUTPUT SPECIFICATIONS

Signal Name	Pin	Output Voltage	Output Current	Protected Voltage	ESD Tolerance
Analog Out	30	0 to 10 V	10 mA	–1 V to (MaxV + 10 V)	± 8 kV (direct strike)

Power Supply Outputs

Quick Links:
Figure 3 wiring diagram p.12

Two lines provide auxiliary output power for low power circuits such as electronic throttles, LED indicators, displays, position encoder, and remote I/O boards. I/O Ground (at pin 7) is the return line for these low power devices. Both power supply outputs are protected against shorts to B+ or B–.



POWER SUPPLY OUTPUT SPECIFICATIONS

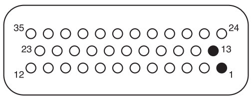
Signal Name	Pin	Output Voltage	Output Current	Protected Voltage	ESD Tolerance
+12 V Out	25	11.5 to 14.5 V	100 mA max for +12 Out 100 mA max for +5 Out 200 mA max (combined total)	–1 V to (MaxV + 10 V)	± 8 kV (direct strike)
+5 V Out	26	5 V ±10%			
I/O Ground	7	n/a	500 mA max	not protected	

KSI and Coil Return

The KSI input provides power for all low power control circuits. This includes the microprocessors, power supply outputs, power for the digital and PWM driver outputs, the power-capacitor precharge (before main contactor closure). Battery voltage is sensed on the input for the VCL battery discharge function.

Coil Return (pin 13) should be wired to the positive battery side of the contactors being driven so that switching noise associated with PWM operation of the contactors is localized to the contactor wiring only.

It is important to maintain the division between KSI and coil return in order to ensure reverse polarity protection (e.g., vehicle wiring correct, battery terminals reversed).



KSI and COIL RETURN INPUT SPECIFICATIONS

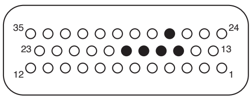
Signal Name	Pin	Operating Voltage	Input Current	Protected Voltage	ESD Tolerance
KSI	1	Between under- and overvoltage cutbacks	13 A max * continuous	± (MaxV + 10 V)	± 8 kV (direct strike)
Coil Return	13		10 A or 12 A max **	(KSI – 0.3 V) to (MaxV + 10 V)	

** Including current from the coil return (pin 13).*
*** 12 A for 1236E/SE and 1238E/SE; 10 A for 1232E/SE and 1234E/SE.*

Throttle and Brake Inputs

The two pot inputs are independently programmable to allow use of a voltage throttle or a 2-wire or 3-wire resistance throttle. Voltage throttles require only the Pot Wiper input (with I/O Ground for the return line). Resistance throttles require Pot Wiper and Pot Low (2-wire) or Pot High, Pot Wiper, and Pot Low (3-wire). All throttle I/O is protected against shorts to B+ or B–.

Alternatively, these two inputs can be used for analog signals other than the throttle and brake pot inputs. Configuring the inputs for use with other signals requires VCL programming; see Chapter 10.



Quick Links:
Figure 3 wiring diagram p.12
Throttle & Brake Types p.20–23

THROTTLE INPUT SPECIFICATIONS

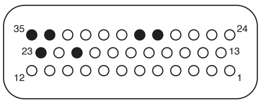
Signal Name	Pin	Operating Voltage	Input Impedance	S/Sink Current	Protected Voltage	ESD Tolerance
Throttle Pot High	15	0 V (shorted to Pot Low) 5 V (open circuit)	N/A	1 mA nominal (source)	−0.5 V to (MaxV + 10 V)	± 8 kV (direct strike)
Pot2 High	27					
Throttle Pot Wiper	16	0 to 6.25 V	100 kΩ min	0.76 mA nominal (source, 2-wire)		
Pot2 Wiper	17					
Pot Low	18	0 to 0.25 V	20 Ω nom.	Faults if above 15 mA (sink)	−1 V to (MaxV + 10 V)	

Communications Ports

Separate CAN and serial ports provide complete communications and programming capability for all user available controller information.

The Curtis 1313 handheld programmer and 1314 PC programmer's 1309-serial-interface-device plug into a connector* wired to pins 28 and 29, along with ground (pin 7) and the +12 V power supply (pin 25); see wiring diagram, Figure 3. The Curtis "Spy" Model 840 display will connect the the serial-port pins as shown in Figure 3.

Wiring the CAN Term H and CAN Term L pins together provides a local CAN termination of 120 Ω, 0.5 W; keep the length of these wires short. CAN Term H and CAN Term L should never be connected to any external wiring.



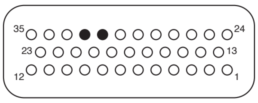
COMMUNICATIONS PORT SPECIFICATIONS

Signal Name	Pin	Supported Protocol / Devices	Data Range	Protected Voltage	ESD Tolerance
CAN H	23	CANopen, other 11-bit or 29-bit identifier protocols	up to 1 Mbit/s	−0.5 V to (MaxV + 10 V)	± 8 kV (direct strike)
CAN L	35				
CAN Term H	21			(no connection to external wiring)	
CAN Term L	34				
Serial TX	28	Curtis 840 Display, 1313 Handhelp Programmer, 1314 PC Programming Station	as required, 9.6 kbit/s to 56 kbit/s	−0.3 V to 12 V	
Serial RX	29				

** Molex Mini-Fit Jr. dual-row, 4 circuits, vehicle harness plug (e.g., p/n 39-01-2046)*

Position Feedback Input: Quadrature Encoder

Two control lines are internally configured to read a quadrature type position encoder. The encoder is typically powered from the 5 V supply (pin 26) or 12 V supply (pin 25), but can be powered from any external supply (from 5 V up to B+) as long as the logic threshold requirements are met. The quadrature encoder is used in ACIM applications.



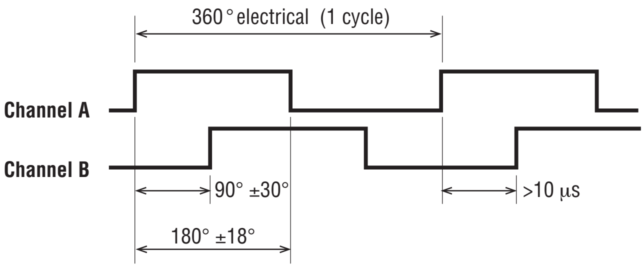
QUADRATURE ENCODER INPUT SPECIFICATIONS

Signal Name	Pin	Logic Threshold	Input Impedance	Max. Frequency	Protected Voltage	ESD Tolerance
Position Feedback A	31	Rising edge= 2.9 V max Falling edge= 2.0 V min	2 kΩ (internal pull-up to to +4.5 V)	10 kHz	–5 V to (MaxV + 10 V)	± 8 kV (direct strike)
Position Feedback B	32					

Phase Shift 90° ±30, Duty Cycle 50% ±10%; no signal edge can be closer than 10 μs to an adjacent edge.

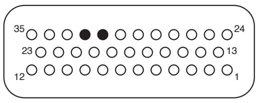
Quick Links:
Figure 3 wiring diagram p.12

These signal tolerances must be maintained throughout the application's operating conditions, including voltage, temperature, speed and torque ranges.



Position feedback input: Sin/Cos sensor

Two control lines are internally configured to read a Sin/Cos sensor. Position Feedback A (pin 31) provides the sine signal, and Feedback Position B (pin 32) provides the cosine signal. The device must be set up with one sensor revolution per mechanical revolution. The Sin/Cos sensor is used in SPM applications.

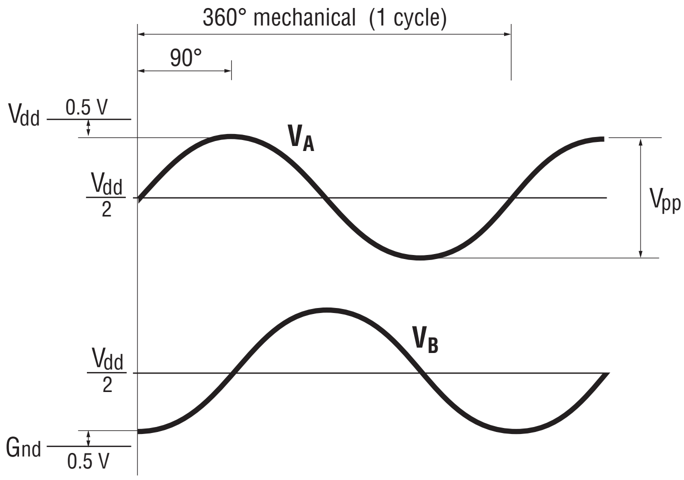


SIN/COS SENSOR INPUT SPECIFICATIONS

Signal Name	Pin	Operating Voltage	Input Impedance	Max. Frequency	Protected Voltage	ESD Tolerance
Position Feedback A	31	0 to 5 V	150 kΩ for voltages ≤ 5 V 75 kΩ for voltages > 5 V	500 Hz	–5 V to (MaxV + 10 V)	± 8 kV (direct strike)
Position Feedback B	32					

Quick Links:
Figure 3 wiring diagram p.12

These signal tolerances must be maintained throughout the application's operating conditions, including voltage, temperature, speed and torque ranges. The Sin/Cos waveform peaks must be away from V_{dd} and ground by at least 0.5 V. In the example shown in the timing diagram below, V_{dd} = 5 V.



3 — APPLICATION-SPECIFIC FEATURES

Some features of the 1232E/SE – 1238E/SE controllers affect how the specific controller is wired or parameter settings. This chapter provides background information on application-specific features, to assist the vehicle designer in the design process.

THROTTLE WIRING

In this manual, the term *throttle* is used in two senses: (1) as another name for the drive throttle, and (2) as a generic term covering both the drive throttle and the brake throttle. Wiring is the same, whether the throttle in question is used for acceleration or (regen) braking.

Various throttles can be used with these controllers. They are characterized as one of five types in the programming menu of the 1313/1314 programmer.

Type 1: 2-wire 5kΩ–0 potentiometers
Type 2: single-ended 0–5V throttles, current source throttles, 3-wire potentiometers, and electronic throttles
Type 3: 2-wire 0–5kΩ potentiometers
Type 4: wigwag 0–5V throttles and 3-wire potentiometers
Type 5: VCL input (VCL_Throttle or VCL_Brake)

The two throttle inputs (drive throttle and brake throttle) are programmed independently.

For potentiometers, the controller provides complete throttle fault protection that meets all applicable EEC regulations. **For voltage throttles,** the controller protects against out-of-range wiper values, but does not detect wiring faults; it is therefore the responsibility of the OEM to provide full throttle fault protection in vehicles using voltage throttles.

Quick Links:
Figure 15 p.105

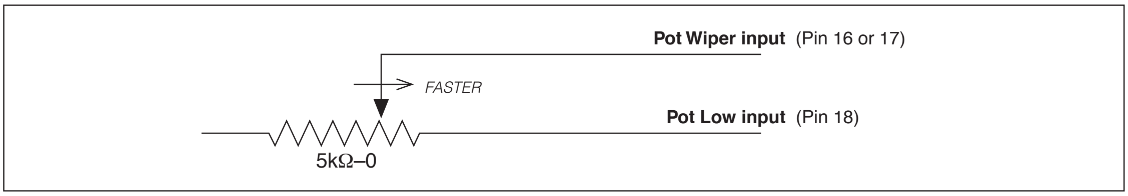
Throttle types 1–3 use the forward and reverse inputs (switches 7 and 8) in addition to the throttle pot input to define the throttle command (see Figure 15). Throttle types 4 and 5 do not use the forward and reverse inputs.

Wiring for the most common throttles is described in the following three pages and shown in the accompanying illustrations. If a throttle you are planning to use is not covered, contact your Curtis distributor or support engineer.

Throttle Type 1

For these 2-wire resistive potentiometers, shown in Figure 4, full throttle request corresponds to 0 Ω measured between the pot wiper pin and the Pot Low pin. A Type 1 throttle requires the Forward & Reverse Deadbands parameters settings be towards the higher voltage (e.g., 4.50 V) and the Forward & Reverse Max parameters set to the lower voltage (e.g., 0.5 V). Note, this is the opposite of these parameters' default setting. With the 2-wire rheostat in place, the throttle-wiper voltage can be check using the Monitor » Inputs variable Throttle Pot (or Pot2Raw for the brake pot).

Figure 4
Wiring for Type 1 throttles.



Broken wire protection is provided by the controller sensing the current flow from the pot wiper input (pin 16 or 17) through the potentiometer and into Pot Low (pin 18). For Type 1 throttles, if the Pot Low input current falls below 0.65 mA, a throttle fault is generated and the throttle request is zeroed. Note: Pot Low (pin 18) must not be tied to ground (pin 7 or B–).

Throttle Type 2

With these throttles, the controller looks for a voltage signal at the wiper input. Zero throttle request corresponds to 0 V and full throttle request to 5 V.

A variety of devices can be used with this throttle input type, including voltage sources, current sources, 3-wire pots, and electronic throttles. The wiring for each is slightly different, as shown in Figure 5, and they have varying levels of throttle fault protection.

When a **voltage source** is used as a throttle, it is the responsibility of the OEM to provide appropriate throttle fault detection. For ground-referenced 0–5V throttles, the controller will detect open breaks in the wiper input but cannot provide full throttle fault protection.

To use a **current source** as a throttle, a resistor must be added to the circuit to convert the current source value to a voltage; the resistor should be sized to provide a 0–5V signal variation over the full current range. It is the responsibility of the OEM to provide appropriate throttle fault detection.

When a **3-wire potentiometer** is used, the controller provides full fault protection in accordance with EEC requirements. The pot is used in its voltage divider mode, with the controller providing the voltage source and return. Throttle Pot High (pin 15) provides a current limited 5V source to the 3-wire potentiometer, and Pot Low (pin 18) provides the return path. This is the throttle shown in the basic wiring diagram (Figure 3) for the drive throttle and for the brake throttle.

Complementing the controllers, Curtis offers both Hall-effect and 3-wire potentiometer throttles which are easily integrated into vehicles.

Hall-effect voltage throttles:

The Curtis FP Series of throttles offers multiple pedal angles and mounting configurations (floor, suspended, flush) with 0–5 Volt operation with a Idle Validation Switch (IVS).

The ET-XXX electronic throttle is typically used only as a drive throttle (illustrated in Fig. 5).

These voltage throttles contains no built-in fault detection, and the controller will detect only open wiper faults. It is the responsibility of the OEM to provide any additional throttle fault detection necessary.

3-wire potentiometer throttle:

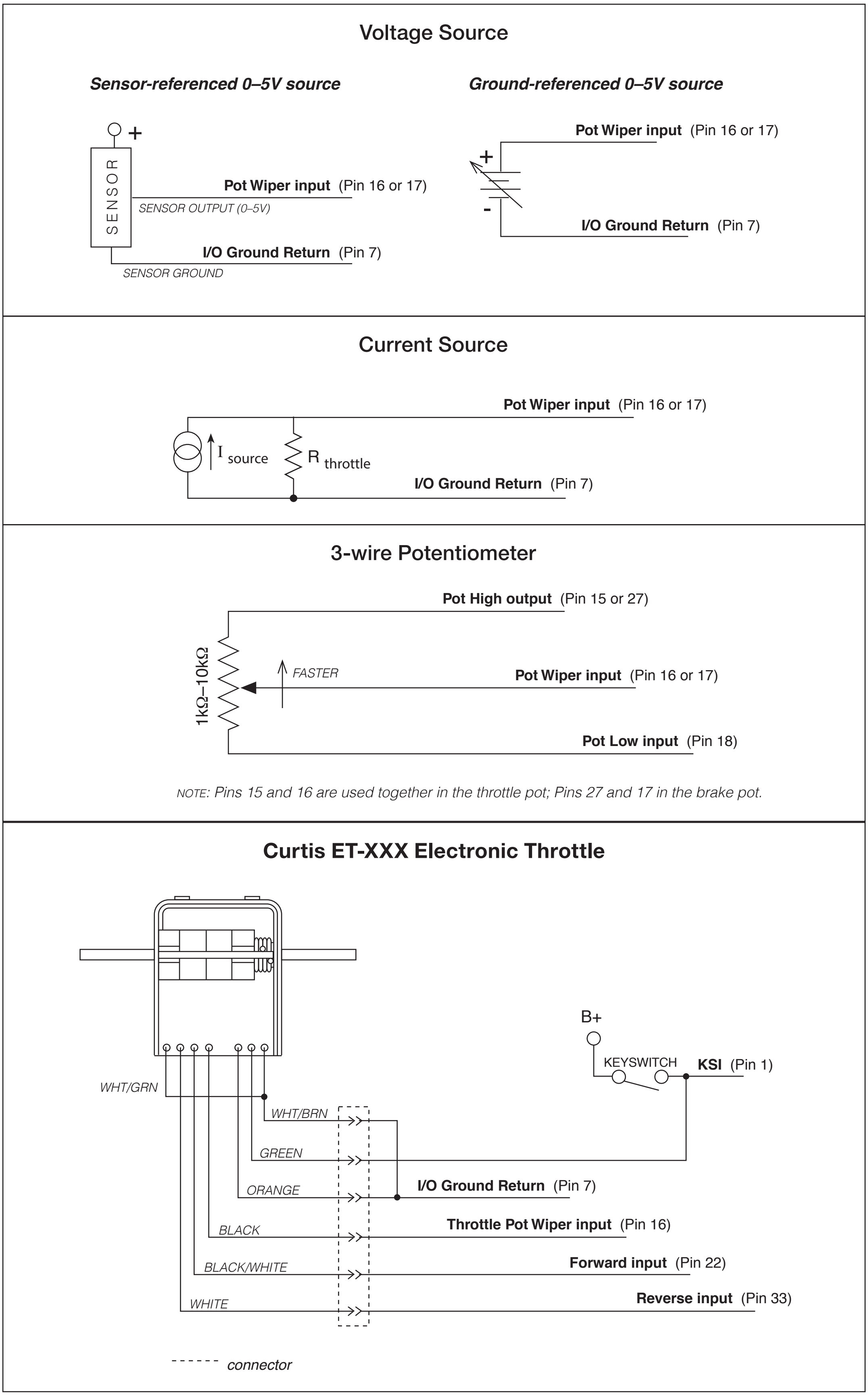
The FP-10 model offers, besides the controller’s 3-wire fault detection, two throttle spring detection switches and two micro-switches to indicate idle validation and full throttle circuits. This throttle can also be configured from 0-5k (Type 3) or 5k-0 (Type 1) throttles while retaining the detection circuits.

For help with a throttle selection, contact your Curtis distributor or support engineer to discuss your particular throttle requirements and the application of Curtis throttles.

Curtis FP-SCV-0022 Hall-effect throttle

Figure 5

Wiring for Type 2 throttles.



Voltage Source

Sensor-referenced 0–5V source

Ground-referenced 0–5V source

Current Source

3-wire Potentiometer

Curtis ET-XXX Electronic Throttle

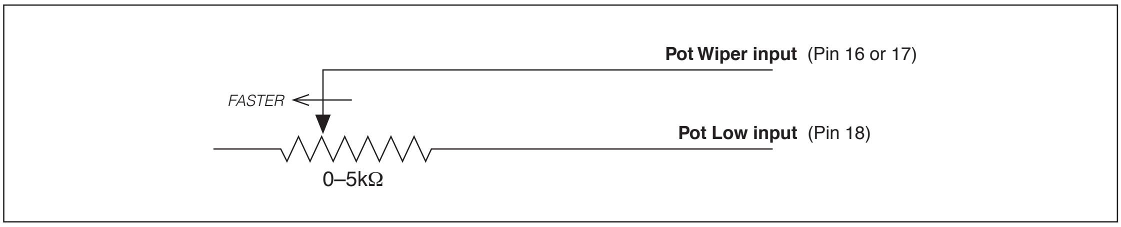
NOTE: *Pins 15 and 16 are used together in the throttle pot; Pins 27 and 17 in the brake pot.*

Throttle Type 3

For these 2-wire resistive potentiometers, shown in Figure 6, full throttle request corresponds to 5 kΩ measured between the pot wiper pin and the Pot Low pin.

Figure 6

Wiring for Type 3 throttles.



Broken wire protection is provided by the controller sensing the current flow from the wiper input (pin 16 or 17) through the potentiometer and into Pot Low (pin 18). For Type 3 throttles, if the Pot Low input current falls below 0.65 mA, a throttle fault is generated and the throttle request is zeroed. Note: Pot Low (pin 18) must not be tied to ground (pin 7 or B–).

Throttle Type 4

Type 4 throttles operate in wigwag style. No signals to the controller's forward and reverse inputs are required; the direction is determined by the wiper input value. Only 0–5V voltage sources and 3-wire potentiometers can be used as Type 4 throttles. The controller interface for Type 4 throttles is the same as for the corresponding Type 2 throttles; see Figure 5.

In a Type 4 throttle, the neutral point must be set up somewhere in the center of the throw, with increasing voltage beyond this point providing increasing forward command and voltages below this point providing increasing reverse command. For example, you might set the Forward Deadband at 2.6 V with Forward Max at 4 V, and Reverse Deadband at 2.4 V with Reverse Max at 1 V.

When a 3-wire pot is used, the controller provides full fault protection. When a voltage throttle is used, the controller will detect open breaks in the wiper input but cannot provide full throttle fault protection.

Throttle Type 5

Quick Links:
Figure 15 p.105
Throttle Type parameter p.46
Brake Type parameter p.48

Throttle Type 5 provides a different way of sending the throttle command to the controller. This throttle type uses VCL to define the throttle signal that will be "input" into the throttle signal chain as VCL_Throttle (see Figure 15).

This throttle type can be used for either the drive throttle or the brake throttle by using the VCL variables VCL_Throttle or VCL_Brake (see Brake menu). How the VCL program is written will determine the source of the throttle signal, making this a very flexible throttle input method. VCL can be written to use the throttle or brake pot inputs, switch inputs, or CAN communication messages as the source of the throttle signals.

Setting the Throttle Type to Type 5 also allows the throttle pot input (Pin 16) to be redefined by a VCL program for uses other than throttle input.

Note: The option also applies to the Brake Type, which when set to Type 5 uses VCL_Brake as signal chain for the Brake_Command (see the Brake parameter menu and Figure 15)

If you have questions regarding this throttle type, contact your Curtis distributor or support engineer.

MOTOR SPEED CONSTRAINTS

The maximum motor speed is a programmable parameter in each control mode. Regardless of which control mode is used, the maximum motor speed the controller will allow is constrained by the number of motor poles, the encoder pulses per motor revolution, and the maximum speed constraint imposed by the firmware.

NOTE: The overall maximum motor speed* allowed is the least of the following three constraints:

1. Electrical Frequency Constraint

The controller is designed to output fundamental electrical frequencies up to 450 Hz. It accomplishes this by clamping the Max Speed allowed, using the equation:

Max Speed Frequency Limit = 54000 / Number of Motor Poles

Thus, for example, an 8-pole motor running synchronously at 450 Hz would rotate at 54000/8 = 6730 rpm (max). Therefore the internal control software will limit the max speed to 6750 rpm for an 8-pole motor. Limited over-speed is allowed, for example if the motor were to go over this speed going down a hill, the controller will still attempt to produce the correct frequency for maximized torque and proper control; it will not simply clamp to 450 Hz.

2. Encoder Pulses/Revolution Constraint (quadrature encoder)

The maximum encoder frequency the controller will accept is 10 kHz. To determine how fast this constraint will allow your motor to spin, use the equation

Max Speed Encoder Limit = 600000 / Encoder Size
(e.g., a motor with a 128-pulse encoder can run up to 4687 rpm).

Quick Links:
Max Speed Controller Limit p.73

3. Firmware Max Speed Constraint

The maximum motor speed the controller will allow is 8000 rpm.

Max Speed RPM Limit = 8000*

** This maximum allowed speed is displayed in the Monitor » Motor » Max Speed Controller Limit variable*

Note: In the case where the Max Speed parameter is the prevailing constraint, greater RPM may be possible.

Contact your Curtis distributor or support engineer to discuss your particular application.

VOLTAGE LIMITS

The controller establishes both hardware-based voltage limits and parameter-based user defined limits. Overvoltage protection cuts back regen braking to prevent damage to batteries and other electrical system components due to overvoltage. Undervoltage protection prevents systems from operating at voltages below their design thresholds

The four threshold points are calculated from the Nominal Voltage, Undervoltage Kp and Ki, User Overvoltage, and User Undervoltage parameter settings and the controller's minimum voltage and maximum voltage ratings. Note that both the KSI (pin 1) and the B+ terminal (when the main is closed) are at battery voltage, and the capacitor bank is precharged via KSI prior to the main closure.

Quick Links:
Controller voltage ratings p.147
User/parameter voltage limits p.62

Overvoltage = Either Max Voltage (see Table D-1) or *User Overvoltage* × *Nominal Voltage,* whichever is lower.

Severe Overvoltage = Overvoltage (see previous item) + 10V.

Undervoltage = Either Min Voltage (see Table D-1) or *User Undervoltage* × *Nominal Voltage,* whichever is higher.

Severe Undervoltage = Either drive current cut back to 0% for 64 ms or Brownout Voltage * (see Table D-1) is reached, whichever comes first.

---

* The Brownout Voltage is determined by the controller base type and cannot be changed. When the controller's capacitor voltage falls below the Brownout voltage the bridge is switched off (i.e., motor current is switched off). If the capacitor voltage stays below the Brownout voltage for > 64 milliseconds the controller will reset (equivalent to cycling the keyswitch). If the capacitor voltage rises above the Brownout voltage before 64 ms have passed the bridge will be re-enabled. The Severe Undervoltage point cannot be set lower than the Brownout voltage.

BATTERY DISCHARGE INDICATOR

The lead-acid battery discharge indicator (BDI) algorithm continuously calculates the battery state-of-charge from the B+ voltage, whenever the main contactor is closed. The result of the BDI algorithm is the variable BDI Percentage, which is viewable in the 1313/1314 menu Monitor » Battery. When KSI is turned off, the present BDI Percentage is stored in nonvolatile memory.

The standard values for volts per cell are as follows, for flooded lead-acid batteries and sealed maintenance-free lead-acid batteries.

	Battery Type	
	Flooded	**Sealed**
Reset Volts Per Cell	2.09	2.09
Full Volts Per Cell	2.04	2.04
Empty Volts Per Cell	1.73	1.90

Use the standard values for your type of batteries as the starting point in setting the reset, full, and empty volts-per-cell parameters. Note: For non lead-acid batteries, including Lithium-Ion battery packs, use the pack's or cell manufacturer's approved Battery Management System (BMS) for determining BDI.

4 — PROGRAMMABLE PARAMETERS

These controllers have a number of parameters that can be programmed using a Curtis 1313 handheld programmer or 1314 PC Programming Station. The programmable parameters allow the vehicle's performance to be customized to fit the needs of specific applications.

PROGRAMMING MENUS

The programmable parameters are grouped into nested hierarchical menus, as shown in Table 3.

Motor response tuning

Motor response characteristics can be tuned through speed control or through torque control, depending on the application. Use the Control Mode Select parameter (page 31) to select which tuning mode you will use:

- Speed Mode Express
- Speed Mode
- Torque Mode.

Speed Mode Express is a simplified version of Speed Mode with a reduced set of parameters that is adequate for most speed-controlled applications.

Use *Speed Mode* or *Speed Mode Express* for applications where throttle input corresponds to motor speed output.

Use *Torque Mode* for applications where throttle input corresponds to motor torque output.

Note: You can tune using torque control or speed control, but not both. For example, if you adjust a torque control parameter while Speed Mode or Speed Mode Express has been selected as your tuning mode, the programmer will show the new setting but it will have no effect.

We strongly urge you to read Chapter 6, Initial Setup, before adjusting any of the parameters.

NOTICE

Even if you opt to leave most of the parameters at their default settings, it is imperative that you perform the procedures outlined in Chapter 6, which set up the basic system characteristics for your application.

Parameter change faults

Parameters marked **PCF** in the menu charts will set a Parameter Change Fault (code 49) if they are changed while the motor bridge is enabled (interlock = On). Although the parameter will be changed, the fault will prevent motor control functions until the fault is cleared by cycling the keyswitch. If the motor bridge is disabled (interlock = Off), changing these parameters will not cause a fault and the changes will take effect immediately.

Table 3 Programmable Parameters Menus: 1313/1314 Programmer

CONTROL MODE SELECT................ p. 31

0 - SPEED MODE EXPRESS............. p. 31

- Max Speed
- Kp
- Ki
- Accel Rate
- Decel Rate
- Brake Rate
- Pump Enable
- Regen Lower Enable

1 - SPEED MODE MENU...................... p. 32

- SPEED CONTROLLER........... p. 32
    - Max Speed
    - Kp
    - Ki LS
    - Ki HS
    - VEL FEEDFORWARD..... p. 33
        - Kvff
        - Build Rate
        - Release Rate
    - ACC FEEDFORWARD .... p. 34
        - Kaff
        - Kbff
        - Build Rate
        - Release Rate
- RESPONSE.......................... p. 35
    - Full Accel Rate HS
    - Full Accel Rate LS
    - Low Accel Rate
    - Neutral Decel Rate HS
    - Neutral Decel Rate LS
    - Full Brake Rate HS
    - Full Brake Rate LS
    - Low Brake Rate
    - FINE TUNING............ p. 36
        - Partial Decel Rate
        - HS (High Speed)
        - LS (Low Speed)
        - Reversal Soften
        - Max Speed Accel
        - Max Speed Decel
- RESTRAINT............................. p. 37
    - Restraint Forward
    - Restraint Back
    - Soft Stop Speed
    - POSITION HOLD............... p. 38
        - Position Hold Enable
        - Position Hold Timeout Time
        - Kp
        - Kd
        - Zero Speed Threshold
        - Zero Speed Threshold Time
        - Position Hold Settling Time
        - Entry Rate
        - Exit Rollback Reduction
    - Pump Enable.................... p. 39
    - Regen Lower Enable.......... p. 39

2 - TORQUE MODE MENU

- SPEED LIMITER........................ p. 39
    - Max Speed
    - Kp
    - Ki
    - Kd
- RESPONSE .... p. 40
    - Accel Rate
    - Accel Release Rate
    - Brake Rate
    - Brake Release Rate
    - Neutral Braking
    - Neutral Taper Speed
    - Forward Full Restraint Speed
    - Back Full Restraint Speed
    - FINE TUNING...................... p. 41
        - Creep Torque
        - Brake Full Creep Cancel
        - Creep Build Rate
        - Creep Release Rate
        - Gear Soften
        - Brake Taper Speed
        - Reversal Soften
        - Max Speed Decel

CURRENT LIMITS MENU.................. p. 43

- Drive Current Limit
- Regen Current Limit
- Brake Current Limit
- EMR Current Limit
- Interlock Brake Current Limit
- POWER LIMITING MAP.......... p. 43
    - PL Nominal Speed
    - Delta Speed
    - DRIVE LIMITING MAP..... p. 44
        - Nominal
        - Plus Delta
        - Plus 2x Delta
        - Plus 4x Delta
        - Plus 8x Delta
    - REGEN LIMITING MAP... p. 45
        - Nominal
        - Plus Delta
        - Plus 2x Delta
        - Plus 4x Delta
        - Plus 8x Delta

THROTTLE MENU............................. p. 46

- Throttle Type
- Forward Deadband
- Forward Map
- Forward Max
- Forward Offset
- Reverse Deadband
- Reverse Map
- Reverse Max
- Reverse Offset
- Throttle Filter
- HPD SRO Type
- Sequencing Delay
- VCL Throttle Enable

BRAKE MENU.................................. p. 48

- Brake Pedal Enable
- Brake Type
- Brake Deadband
- Brake Map
- Brake Max
- Brake Offset
- Brake Filter
- VCL Brake Enable

Table 3 Programmable Parameters Menus: 1313/1314 Programmer continued

EM BRAKE CONTROL MENU..... p. 49

- Brake Type
- Pull In Voltage
- Holding Voltage
- Battery Voltage Comp.
- Set EM Brake On Fault
- Zero Speed Threshold
- Zero Speed Threshold Time
- Position Hold Settling Time
- Brake Set Time
- Torque Release Time
- Brake Release Time
- Torque Preload Time
- Torque Preload Enable
- Save Torque Preload
- Torque Preload Cancel Delay
- EM Brake Fault Motor Revs

DRIVERS MENU....................... p. 51

- MAIN CONTACTOR......... p. 51
  - Main Enable
  - Main Interlock Type
  - Pull In Voltage
  - Holding Voltage
  - Battery Voltage Comp.
  - Interlock Type
  - Open Delay
  - Weld Check Enable
  - Main DNC Check Enable
  - Main DNC Check Threshold
  - Precharge Enable
- PROPORTIONAL DRIVER... p. 53
  - PD Enable
  - Hyd Lower Enable
  - PD Max Current
  - PD Min Current
  - PD Dither %
  - PD Dither Period
  - PD Kp
  - PD Ki
- DRIVER 3..................... p. 53
  - Contactor Enable
  - Pull In Voltage
  - Holding Voltage

- FAULT CHECKING........................ p. 54
  - Driver1 Checks Enable
  - Driver2 Checks Enable
  - Driver3 Checks Enable
  - Driver4 Checks Enable
  - PD Checks Enable
  - External Supply Max
  - External Supply Min
- PWM FREQUENCY....................... p.54

MOTOR MENU....................................... p. 54

- Typical Max Speed
- CONTROL ALGORITHMS.................. p. 55
  - Motor Technology
  - 0-ACIM (INDUCTION MOTOR)........ p. 55
    - CHARACTERIZATION TEST........ p. 55
      - Test Enable
      - Test Throttle
      - Motor Poles
      - Max Test Speed
      - Max Text Current
      - SlipGain
      - Current Reg Tuning Test Enable
    - FIELD WEAKENING CONTROL... p. 56
      - FW Base Speed
      - Field Weakening Drive
      - Weakening Rate Drive
      - Min Field Current
    - Swap Two Phases.................. p. 57
    - MotorType............................. p. 57
    - LOS (Limited Operating Strategy)... p. 58
      - LOS Upon Encoder Fault
      - LOS Max Speed
      - LOS Max Current
      - LOS Max Mod Depth
      - LOS Accel Rate
      - LOS Decel Rate
  - 1-SPM (SURFACE PM MOTOR)...... p. 59
    - CHARACTERIZATION TESTS...... p. 59
      - Test Enable
      - Test Throttle
      - Max Test Speed
      - Max Test Current

- MOTOR FEEDBACK OPTIONS............. p. 59
  - Feedback Type
  - Swap Feedback Direction
  - 1-ENCODER................................ p 59
    - Encoder Steps
    - ENCODER FAULT SETUP.......... p. 60
      - Fault Detection Enable
      - Encoder Pulse Fault Detect Time
      - Fault Stall Time
  - 2-SIN/COS................................. p. 60
    - Sin Cos Fault Threshold
    - Sin Cos Fault Threshold High
    - Sin Cos Fault Time
    - Sin Min
    - Sin Max
    - Cos Min
    - Cos Max
  - TEMPERATURE CONTROL............. p. 61
    - Sensor Enable
    - Sensor Type
    - Sensor Offset
    - Braking Thermal Cutback Enable
    - Temperature Hot
    - Temperature Max
    - MotorTemp LOS Max Speed

BATTERY MENU................................ p. 62

- Nominal Voltage
- Kp UV
- Ki UV
- User Overvoltage
- User Undervoltage
- Reset Volts Per Cell
- Full Volts Per Cell
- Empty Volts Per Cell
- Discharge Time
- BDI Reset Percent

DUAL DRIVE MENU .... *see Dual Drive addendum, Document number: 53097 DUAL-DRIVE SUPPLEMENT_os31.*

Table 3 Programmable Parameters Menus: 1313/1314 Programmer continued

VEHICLE MENU................................. p. 64

- — Metric Units
- — Speed to RPM
- — Capture Speed 1
- — Capture Speed 2
- — Capture Distance 1
- — Capture Distance 2
- — Capture Distance 3

EMERGENCY REVERSE MENU .... p. 65

- —EMR Enable
- —EMR Type
- —EMR Dir Interlock
- —EMR Time Limit
- —EMR Speed
- —EMR Accel Rate
- —EMR Decel Rate

INTERLOCK BRAKING MENU............. p. 66

- — Enable
- — Decel Rate HS
- — Decel Rate LS
- — Interlock Brake Timeout

CAN INTERFACE MENU..................... p. 67

- — CANopen Interlock
- — CAN Node ID 1
- — CAN Node ID 2
- — CAN Node ID 3
- — CAN Node ID 4
- — Supervisor Node ID
- — Baud Rate
- — Heartbeat Rate
- — PDO Timeout Period
- — Emergency Message Rate
- — Suppress CANopen Init

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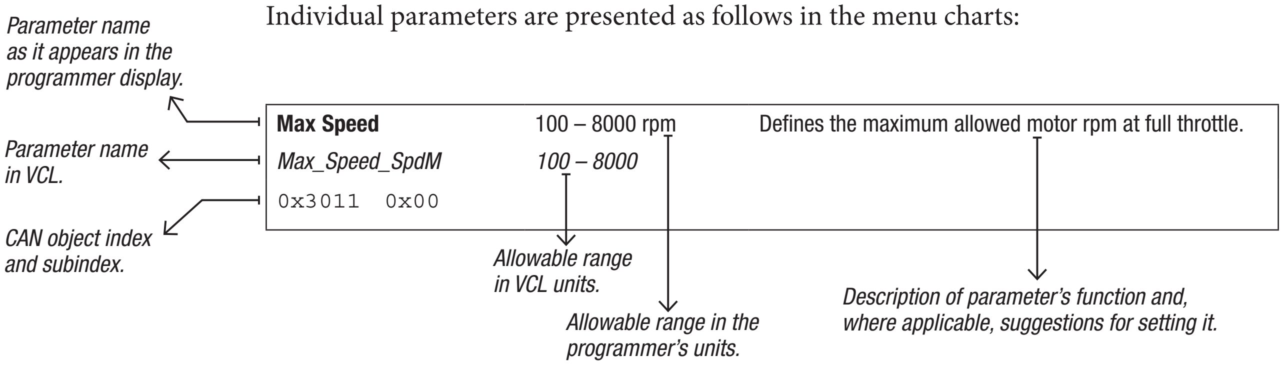
Individual parameters are presented as follows in the menu charts:



Note: All bit variables have two VCL parameter names. The first is the name of the bit, and the second is the name of the byte containing the bit. The bit position within the byte is indicated in brackets after the byte name.

Examples:

BIT NAME: **Metric_Units**
BYTE NAME: *OptionBits3* [Bit 5]
BIT NAME: **EMR_Dir_Interlock**
BYTE NAME: *EMR_DIR_INTERLOCK_BIT0* [Bit 0]

In the second example, "_Bit0" is part of the byte name, and does not indicate the bit position; this byte, like all bytes, has 8 available bits.

Within the menu charts, each pair of bit variable names is shown as a grouped set, with the bit name appearing first and then the byte name:

Metric Units **On/Off**
Metric_Units *On/Off*
OptionBits3 [Bit 5]

SDO Write Message

To retain parameter values changed via CANopen SDO write messages following a key-cycle, write a non-zero value to CAN_EE_Writes_Enabled (object index 0x332F, subindex 0x00) before changing parameter values. This will cause changes to be written to non-volatile memory immediately. After completing the changes, write the value zero to CAN_EE_Writes_Enabled.

CAUTION

Do not leave CAN_EE_Writes_Enabled at a non-zero value during normal operation, because damage to the controller's EEPROM may occur.

CAN SDO and PDO message transmission nomenclature:

Throughout this manual and VCL, CAN messages from the master (server) and messages from the slave (client) controllers are noted as MOSI and MISO versus Rx and Tx. Use the MOSI and MISO in the PDO Byte Map variables as shown on page 78, Monitor » CAN STATUS.

MOSI (Master Out Slave In) = RX (Server to Client), as per CANopen nomenclature.
MISO (Master In Slave Out) = TX (Client to Server), as per CANopen nomenclature.

If you have questions regarding the CAN features, contact your Curtis distributor or support engineer.

CONTROL MODE SELECT

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Control Mode Select PCF *Control_Mode_Select* `0x3010 0x00`	0 – 2 *0 – 2*	This parameter determines which control method will be in effect when programming motor response: **0 = SPEED MODE EXPRESS** **1 = SPEED MODE** **2 = TORQUE MODE** Contact your Curtis distributor or support engineer if you are interested in a custom control method. NOTE: Do not change this parameter while the controller is powering the motor. Any time this parameter is changed a Parameter Change Fault (fault code 49) is set and must be cleared by cycling power; this protects the controller and the operator.

0 - SPEED MODE EXPRESS — SPEED MODE EXPRESS MENU

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Max Speed *Max_Speed_SpdMx* `0x3840 0x00`	100 – 8000 rpm *100 – 8000*	Defines the maximum requested motor rpm at full throttle. Partially-applied throttle is scaled proportionately; e.g., 40% applied throttle corresponds to a request for 40% of the set Max Speed Value. If Max_Speed_SpdMx is set <10 rpm (through VCL or CAN), the throttle request is zeroed NOTE: The maximum motor rpm is subject to the constraints on page 24.
Kp *Kp_SpdMx* `0x3841 0x00`	0 – 100% *0 – 8192*	Determines how aggressively the speed controller attempts to match the speed of the motor to the commanded speed. Larger values provide tighter control. If the gain is set too high, you may experience oscillations as the controller tries to control speed. If it is set too low, the motor may behave sluggishly and be difficult to control.
Ki *Ki_SpdMx* `0x3842 0x00`	5 – 100% *50 – 1000*	The integral term (Ki) forces zero steady state error, so the motor will run at exactly the commanded speed. Larger values provide tighter control. If the gain is set too high, you may experience oscillations as the controller tries to control speed. If it is set too low, the motor may take a long time to approach the exact commanded speed.
Accel Rate *Accel_Rate_SpdMx* `0x3843 0x00`	0.1 – 30.0 s *100 – 30000*	Sets the rate (in seconds) at which the speed command increases when throttle is applied. Larger values represent slower response.
Decel Rate *Decel_Rate_SpdMx* `0x3847 0x00`	0.1 – 30.0 s *100 – 30000*	Sets the rate (in seconds) that is used to slow down the vehicle when the throttle is reduced. Larger values represent slower response.
Brake Rate *Brake_Rate_SpdMx* `0x3848 0x00`	0.1 – 30.0 s *100 – 30000*	Sets the rate (in seconds) at which the vehicle slows down when brake is applied or when throttle is applied in the opposite direction. Larger values represent slower response.
Pump Enable* *AC_Pump_Enable_SpdM* *AC_Pump_Enable_SpdM_Bit0* **[Bit 0]** `0x3896 0x00`	On / Off *On / Off*	This parameter should be programmed On to operate a pump motor rather than a vehicle drive motor. The speed-controller responsiveness and stability are enhanced for pump-motor applications.
Regen Lower Enable* *Regen_Lower_Enable_SpdM* *Regen_Lower_Enable_SpdM_Bit0* **[Bit 0]** `0x3877 0x00`	On / Off *On / Off*	This parameter works together with Pump Enable as follows: 1) When Pump Enable = On and Regen Lower Enable = On, the pump motor can turn in both the forward and the reverse direction. In this case, the pump can be used as the Lower function (reverse). The pump motor, when “driven in reverse by a load” will also regen current in a similar fashion to a drive-motor regenerative braking. 2) When Pump Enable = On and Regen Lower Enable = Off, the pump motor can turn only in the forward direction. In this case, a hydraulic valve is typically used for the Lower function. 3) When Pump Enable = Off, the Regen Lower Enable parameter has no effect on the control system.

** This parameter appears twice in the parameter menu structure. Changing the value of this parameter affects the same parameter in Speed Mode.*

1- SPEED MODE — SPEED CONTROLLER MENU

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Max Speed *Max_Speed_SpdM* `0x3011 0x00`	100 – 8000 rpm *100 – 8000*	Defines the maximum requested motor rpm at full throttle. Partially-applied throttle is scaled proportionately; e.g., 40% applied throttle corresponds to a request for 40% of the set Max Speed Value. If Max_Speed_SpdM is set <10 rpm (through VCL or CAN), the throttle request is zeroed. NOTE: The maximum motor rpm is subject to the constraints on page 24.
Kp *Kp_SpdM* `0x3012 0x00`	0 – 100% *0 – 8192*	Determines how aggressively the speed controller attempts to match the speed of the motor to the commanded speed. Larger values provide tighter control. If the gain is set too high, you may experience oscillations as the controller tries to control speed. If it is set too low, the motor may behave sluggishly and be difficult to control.
Ki LS *Ki_SpdM* `0x3015 0x00`	5 – 100% *50 – 1000*	The Ki LS parameter sets the Ki for low vehicle speeds. The integral term (Ki) forces zero steady state error, so the motor will run at exactly the commanded speed. Larger values provide tighter control. If the gain is set too high, you may experience oscillations as the controller tries to control speed. If it is set too low, the motor may take a long time to approach the exact commanded speed.
Ki HS *Ki_HS_SpdM* `0x301D 0x00`	5 – 100% *50 – 1000*	The Ki HS parameter sets the integral term (Ki) for high vehicle speeds; see description of Ki LS.

1- SPEED MODE — VELOCITY FEEDFORWARD MENU [OPTIONAL]

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Kvff *Kvff_SpdM* `0x3014 0x00`	0 – 500 A *0 – 5000*	This velocity feedforward term is designed to improve throttle responsiveness and speed controller performance, especially at low speeds. For traction systems, set it to 50–70% of the current needed to maintain a very low speed, unloaded, on flat ground. For a pump system, set it to the lowest load current (i.e., the current running at the minimum load). Alternatively, the responsiveness of a pump speed control loop can be significantly enhanced by using a VCL program to continuously update this parameter to the appropriate value as each pump load is requested.
Build Rate *Vel_FF_Build_Rate_SpdM* `0x3093 0x00`	0.1 – 5.0 s *100 – 5000*	Determines how fast the Kvff term builds up. For traction systems, if you feel or hear the mechanical slop pick up abruptly when you move the throttle from neutral to a very small value, slowing the build rate (i.e., setting it to a higher value) will soften the feel. For a pump system, start with this parameter at the minimum setting. Slowing it down (i.e., setting it to a higher value) will reduce speed overshoot if too much feedforward has been commanded.
Release Rate *Vel_FF_Release_Rate_SpdM* `0x3094 0x00`	0.1 – 5.0 s *100 – 5000*	Determines how fast the Kvff term releases. If the release seems too abrupt, slowing the release rate (i.e., setting it to a higher value) will soften the feel. It should be set fast enough (i.e., at a low enough value) to prevent the vehicle from running on after throttle release.

1- SPEED MODE — ACCELERATION FEEDFORWARD MENU [OPTIONAL]

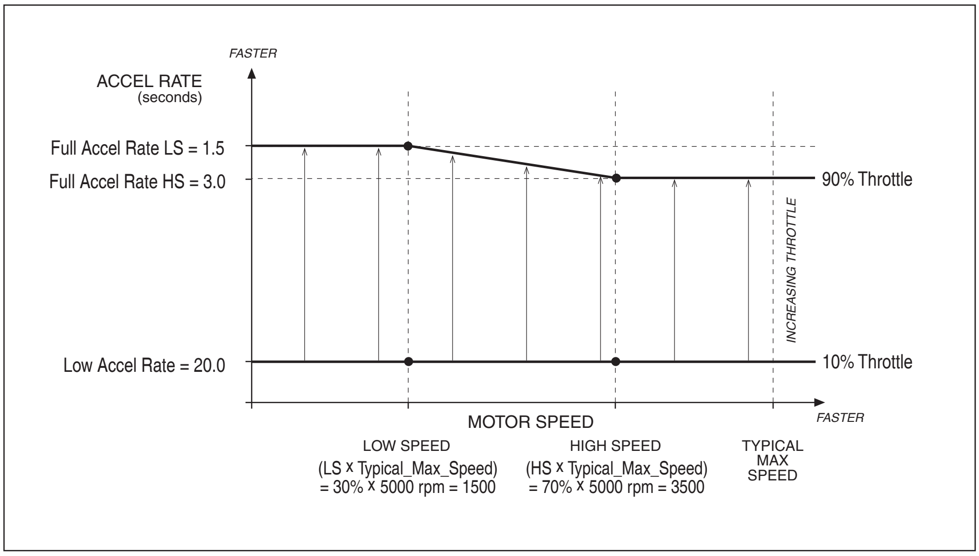
PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Kaff *Kaff_SpdM* `0x3013 0x00`	0 – 500 A *0 – 5000*	This acceleration feedforward term is designed to improve throttle responsiveness and speed controller performance at all speeds. It can be thought of as a "quick start" function which can enhance responsiveness at all speeds. Using your present accel and decel rates, observe the average current you are running at full throttle at low speeds while accelerating without load on flat ground, and set Kaff to 50–70% of that value. **NOTE: If any accel rate parameters get changed, this parameter will need to be changed also.**
Kbff *Kbff_SpdM* `0x3019 0x00`	0 – 500 A *0 – 5000*	This braking feedforward term is designed to improve braking responsiveness at all speeds. Using your present decel rates, observe the average current you are running at full throttle braking, and set Kbff to that value.
Build Rate *Acc_FF_Build_Rate_SpdM* `0x3095 0x00`	0.1 – 5.0 s *100 – 5000*	Determines how fast the Kaff and Kbff terms build up. For traction systems, if you feel or hear the mechanical slop pick up abruptly when you move the throttle from neutral to a very small value, slowing the build rate (i.e., setting it to a higher value) will soften the feel. For a pump system, start with this parameter at the minimum setting. Slowing it down (i.e., setting it to a higher value) will reduce over-shoot if too much feedforward has been commanded.
Release Rate *Acc_FF_Release_Rate_SpdM* `0x3096 0x00`	0.1 – 5.0 s *100 – 5000*	Determines how fast the Kaff and Kbff terms release. It should be set fast enough (i.e., at a low enough value) to prevent the vehicle from running on after throttle release.

1- SPEED MODE —RESPONSE MENU

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Full Accel Rate HS *Full_Accel_Rate_HS_SpdM* `0x307F 0x00`	0.1 – 30.0 s *100 – 30000*	Sets the rate (in seconds) at which the speed command increases when full throttle is applied at high vehicle speeds. Larger values represent slower response. See Figure 7 for relationship between Full Accel Rate HS, Full Accel Rate LS, and Low Accel Rate.
Full Accel Rate LS *Full_Accel_Rate_LS_SpdM* `0x3016 0x00`	0.1 – 30.0 s *100 – 30000*	Sets the rate (in seconds) at which the speed command increases when full throttle is applied at low vehicle speeds.
Low Accel Rate *Low_Accel_Rate_SpdM* `0x3081 0x00`	0.1 – 30.0 s *100 – 30000*	Sets the rate (in seconds) at which the speed command increases when a small amount of throttle is applied. This rate is typically adjusted to affect low speed maneuverability.
Neutral Decel Rate HS *Neutral_Decel_Rate_HS_SpdM* `0x3018 0x00`	0.1 – 30.0 s *100 – 30000*	Sets the rate (in seconds) that is used to slow down the vehicle when the throttle is released to neutral at high vehicle speeds.
Neutral Decel Rate LS *Neutral_Decel_Rate_LS_SpdM* `0x3070 0x00`	0.1 – 30.0 s *100 – 30000*	Sets the rate (in seconds) that is used to slow down the vehicle when the throttle is released to neutral at slow vehicle speeds.
Full Brake Rate HS *Full_Brake_Rate_HS_SpdM* `0x301B 0x00`	0.1 – 30.0 s *100 – 30000*	Sets the rate (in seconds) at which the vehicle slows down from high speeds when full brake is applied or when full throttle is applied in the opposite direction. See Figure 8 for relationship between Full Brake Rate HS, Full Brake Rate LS, and Low Brake Rate.
Full Brake Rate LS *Full_Brake_Rate_LS_SpdM* `0x3077 0x00`	0.1 – 30.0 s *100 – 30000*	Sets the rate (in seconds) at which the vehicle slows down from low speeds when full brake is applied or when full throttle is applied in the opposite direction.
Low Brake Rate *Low_Brake_Rate_SpdM* `0x301A 0x00`	0.1 – 30.0 s *100 – 30000*	Sets the rate (in seconds) at which the vehicle slows down at all speeds when a small amount of brake is applied or when a small amount of throttle is applied in the opposite direction. The Low Brake Rate parameter should always be set less than or equal to the Neutral Decel Rate LS, Neutral Decel Rate HS, Full Brake Rate LS and Full Brake Rate HS.

Figure 7

Acceleration response rate diagram. In this example,
HS = 70%,
LS = 30%,
Typ Max Spd = 5000 rpm.



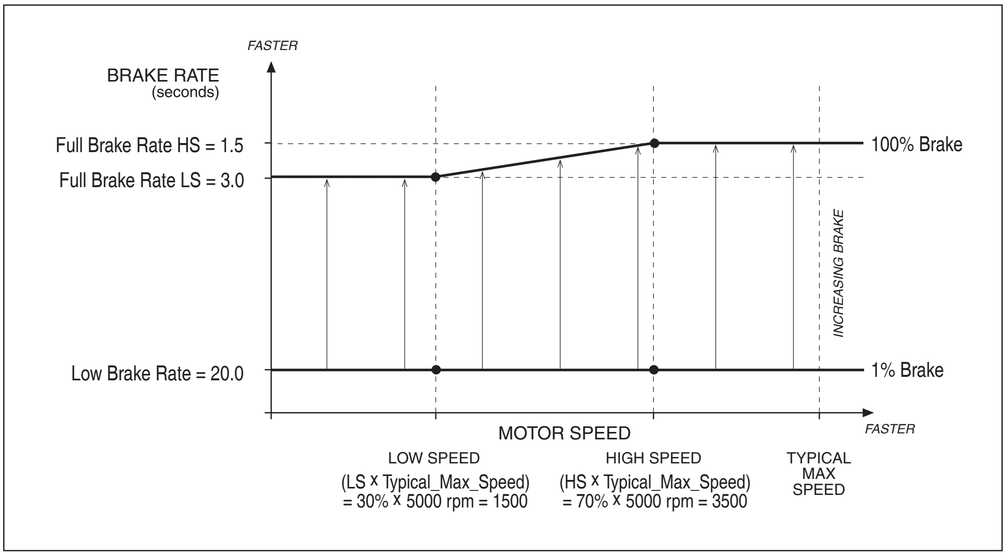
1- SPEED MODE — FINE TUNING MENU

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Partial Decel Rate *Partial_Decel_Rate_SpdM* `0x3082 0x00`	0.1 – 30.0 s *100 – 30000*	Sets the rate (in seconds) that is used to slow down the vehicle when the throttle is reduced without being released to neutral. Larger values represent slower response.
HS (High Speed) *HS* `0x3076 0x00`	0 – 100% *0 – 32767*	Sets the percentage of the Typical Max Speed above which the “HS” parameters will be used.
LS (Low Speed) *LS* `0x3075 0x00`	0 – 100% *0 – 32767*	Sets the percentage of the Typical Max Speed below which the “LS” parameters will be used.
Reversal Soften *Reversal_Soften* `0x3074 0x00`	0 – 100% *0 – 30000*	Larger values create a softer reversal from regen braking to drive when near zero speed. This helps soften the transition when the regen and drive current limits are set to different values. Note: This parameter is not mode-specific and appears in two places. Changing the value of this speed-mode parameter affects the parameter listed in: Program » Torque Mode » Response » Fine Tuning » Reversal Soften.
Max Speed Accel *Max_Speed_Accel_SpdM* `0x384A 0x00`	0.1 – 30.0 s *100 – 30000*	In some applications, the Max Speed value is changed frequently, through VCL or over the CANbus. The Max Speed Accel parameter controls the rate at which the maximum speed setpoint is allowed to change when the value of Max Speed is raised. The rate set by this parameter is the time to ramp from 0 rpm to Typical Max Speed rpm. For example, suppose Max Speed is raised from 1000 rpm to 4000 rpm. If Typical Max Speed is 5000 rpm and the rate is 10.0 seconds, it will take 10.0 X (4000–1000) ÷ 5000 = 6.0 seconds to ramp from 1000 rpm to 4000 rpm.
Max Speed Decel *Max_Speed_Decel_SpdM* `0x3846 0x00`	0.1 – 30.0 s *100 – 30000*	This parameter works like the Max Speed Accel parameter, except that it controls the rate at which the maximum speed setpoint is allowed to change when the value of Max Speed is lowered. For example, suppose you change Max Speed from 4500 rpm to 2500 rpm. If Typical Max Speed is 5000 rpm, and the rate is 5.0 seconds, it will take 5.0 X (4500–2500) ÷ 5000 = 2.0 seconds to ramp from 4500 rpm to 2500 rpm.

Quick Links:
Typical Max Speed p.54

Figure 8

Braking response rate diagram. In this example,
HS = 70%,
LS = 30%,
Typ Max Spd = 5000 rpm.



1- SPEED MODE — RESTRAINT MENU

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Restraint Forward *Restraint_Forward_SpdM* `0x3020 0x00`	0 – 100% *0 – 32767*	Increases torque when on a steep hill in order to limit roll-forward speed. Setting this parameter too high may cause oscillations in the motor as it attempts to limit the roll-forward speed.
Restraint Back *Restraint_Back_SpdM* `0x301F 0x00`	0 – 100% *0 – 32767*	Increases torque when on a steep hill in order to limit roll-back speed. Setting this parameter too high may cause oscillations in the motor as it attempts to limit the roll-back speed.
Soft Stop Speed *Soft_Stop_Speed* `0x3027 0x00`	0 – 500 rpm *0 – 500*	Defines the speed below which a much slower decel rate is used. A setting of zero disables the function. NOTE: This parameter works only in Speed Mode and Speed Mode Express. Soft Stop Speed is useful for vehicles that have fast deceleration and vehicles operating on ramps using the Position Hold function. With vehicles that have fast deceleration, the driver may find the final speed reduction to zero rpm uncomfortable; the vehicle may even rock back as a result of tire wind-up. Soft Stop Speed allows the vehicle to slow at the same fast rate until it reaches the set threshold, at which point it changes to a slower (softer) deceleration rate. However, if the threshold is set too high, the vehicle will feel like it is “running on.” When throttle is released on a ramp, the vehicle may roll back before Position Hold (see below) takes control. Soft Speed Stop can be used to reduce the amount of rollback, but shouldn’t be set so high the vehicle drives up the ramp after the throttle is released.

1- SPEED MODE — POSITION HOLD MENU

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Position Hold Enable **PCF** *Position_Hold_Enable* *Position_Hold_Enable_Bit0* [Bit 0] `0x3893 0x00`	On / Off *On / Off*	Allows the Position Hold mode to be entered at zero throttle when the vehicle comes to a stop. NOTE: EM Brake Type = 2 also enables the Position Hold function
Position Hold Timeout Time *Position_Hold_Timeout_Time* `0x388C 0x00`	0.0 – 20.0 s *0 – 625*	This parameter plus the **Position Hold Settling Time** parameter sets the maximum time the vehicle will stay in Position Hold before releasing the hold and going into Restraint mode. Setting the parameter to zero disables this timeout function, which means the Position Hold will be held. Activating the interlock resets the timer.
Kp *Kp_Position_Hold* `0x388A 0x00`	2 – 100% *82 – 2048*	Determines the stiffness with which position is regulated when in Position Hold mode. High Kp will produce less rollback on a ramp, but more bouncing; see Kd below. Too much Kp will cause instability.
Kd *Kd_Position_Hold* `0x388D 0x00`	0 – 100% *0 – 8192*	Determines the damping in Position Hold mode. Some damping must be present in the control system to keep the vehicle from oscillating slowly (“bouncing”). High Kd will improve the dynamic response of the Position Hold controller, but too much Kd will cause fast instability.
Zero Speed Threshold *Zero_Speed_Threshold* `0x306F 0x00`	5 – 100 rpm *5 – 100*	Determines the speed below which the EM brake will be commanded to set. Setting this speed too high may cause a jerky stop when the EM brake sets and stops the motor. This parameter appears twice in the menu structure. Changing the value of this parameter affects this (same) parameter in the EM Brake Control menu, page 49. ***This parameter is re-named for os31. It is the same as the previous Set Speed Threshold parameter.***
Zero Speed Threshold Time *Zero_Speed_Threshold_Time* `0x30DA 0x00`	0 – 480 ms *0 – 60*	Determines how long motor speed must be below Zero_Speed_Threshold to declare zero speed. This parameter appears twice in the menu structure. Changing the value of this parameter affects this (same) parameter in the EM Brake Control menu, page 49. ***This is a new parameter for os31***
Position Hold Settling Time *Position_Hold_Settling_Time* `0x3024 0x00`	0 – 5000 ms *0 – 156*	Determines how long the position hold function is allowed to operate before the EM brake is set. This time should be set long enough for the position hold to settle. This parameter appears twice in the menu structure. Changing the value of this parameter affects this (same) parameter in the EM Brake Control menu, page 50. ***This parameter is re-named in os31. It is the same as the previous Set Speed Settling Time parameter.***
Entry Rate *Entry_Rate_Position_Hold* `0x383B 0x00`	5 – 100% *50 – 1000*	When the vehicle transitions from forward speed to reverse speed or from reverse speed to forward speed (for example when coming to a stop going up a steep ramp) Position Hold is automatically entered immediately at zero speed regardless of this parameter. This parameter applies when the vehicle needs to be brought to a stop without the assistance of gravity (for example when moving forward down a ramp). This rate determines how quickly zero speed is attained after the ramped speed request reaches zero. Setting this parameter too high will make the stop seem very abrupt and may even cause the vehicle to roll back slightly. When the parameter is set lower the vehicle take longer to come to a stop and enter Position Hold mode.
Exit Rollback Reduction *Exit_Rollback_Reduction* `0x3844 0x00`	0 – 100% *0 – 2048*	This function is applicable when the Torque Preload Enable function has been Disabled (Off) or the Torque Preload Cancel Delay timer has expired (see EM Brake menu). Exit Rollback Reduction is only intended for use with EM Brake Type = 2, for EM Brake Type = 1 (or 0) set Exit Rollback Reduction = 0. Exit Rollback Reduction introduces an additional control function for the speed controller to reduce rollback on a ramp after a throttle command is applied from a stop. For example, suppose the vehicle is on a ramp facing upwards and, after a forward throttle request, the vehicle rolls back slightly before climbing the ramp (again, assuming the torque preload function is inactive). As the vehicle rolls back, this additional term will be added to the torque request until forward speed is sensed, to attempt to minimize rollback. The effect increases with percentage, and is disabled when = 0%. Setting the value too high may introduce temporary oscillations. If the Torque Preload Cancel Delay parameter expires before the throttle is re-engaged, the torque preload [Position Hold] memory will be cleared. In such a case, setting Exit Rollback Reduction to > 0% will reduce unintended roll. (see page 51).

1- SPEED MODE — PUMP PARAMETERS

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Pump Enable* |*AC_Pump_Enable_SpdM* |*AC_Pump_Enable_SpdM_Bit0* **[Bit 0]** `0x3896 0x00`	On / Off *On / Off*	This parameter should be programmed On to operate a pump motor rather than a vehicle drive motor. Speed controller responsiveness and stability are enhanced.
Regen Lower Enable* *Regen_Lower_Enable_SpdM* *Regen_Lower_Enable_SpdM_Bit0* **[Bit 0]** `0x3877 0x00`	On / Off *On / Off*	This parameter works together with Pump Enable as follows: 1) When Pump Enable = On and Regen Lower Enable = On, the pump motor can turn in both the forward and the reverse direction. In this case, the pump can be used as the Lower function (reverse). The pump motor, when “driven in reverse by a load” will also regen current in a similar fashion to a drive-motor regenerative braking. 2) When Pump Enable = On and Regen Lower Enable = Off, the pump motor can turn only in the forward direction. In this case, a hydraulic valve is typically used for the Lower function. 3) When Pump Enable = Off, the Regen Lower Enable parameter has no effect on the control system.

** This parameter appears twice in the parameter menu structure. Changing the value of this parameter affects the same parameter in Speed Mode Express.*

2 – TORQUE MODE — SPEED LIMITER MENU

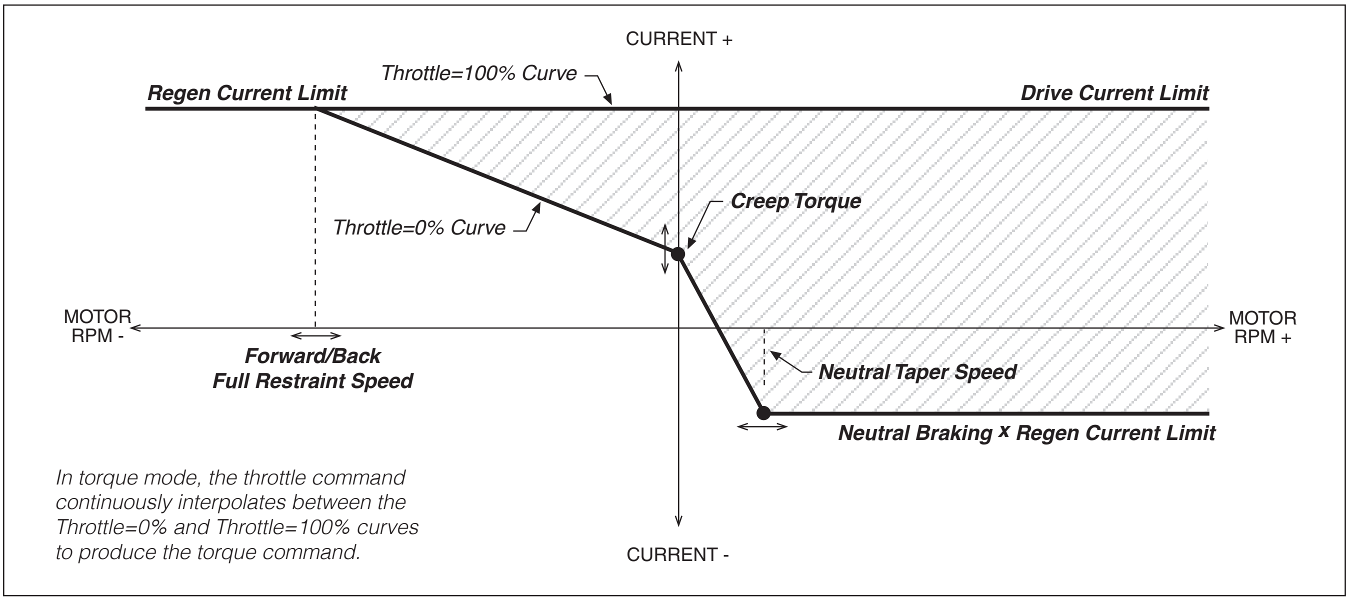
PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Max Speed *Max_Speed_TrqM* `0x3021 0x00`	500 – 8000 rpm *500 – 8000*	Defines the maximum allowed motor rpm for torque control mode (independent of throttle position). In torque control mode, full throttle requests 100% of the available torque. Partially-applied throttle is scaled proportionately; e.g., 40% applied throttle corresponds to a request for 40% of the available torque. NOTE: The maximum motor rpm is subject to the constraints on page 24.
Kp *Kp_TrqM* `0x3023 0x00`	0 – 100% *0 – 8192*	Determines how aggressively the speed controller attempts to limit the speed of the motor to Max Speed. Larger values provide tighter control. If Kp is set too high, you may experience oscillations as the controller tries to control speed. Setting Kp too low may result in a top speed much higher than Max Speed.
Ki *Ki_TrqM* `0x3025 0x00`	5 – 100% *50 – 1000*	The integral term (Ki) forces zero steady state error, so the motor speed will be limited to Max Speed. Larger values provide faster control. If the gain is set too high, you may experience oscillations as the controller tries to limit speed. If it is set too low, it may take a long time for the motor to approach Max Speed from overspeed.
Kd *Kd_TrqM* `0x3836 0x00`	0 – 100% *0 – 8192*	Provides damping as the vehicle approaches top speed, thereby reducing overshoot. If Kd is set too high, the vehicle may take too long to reach top speed. If Kd is set too low, the vehicle may overshoot top speed, especially when traveling downhill.

2 - TORQUE MODE — RESPONSE MENU

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Accel Rate *Accel_Rate_TrqM* `0x3026 0x00`	0.1 – 30.0 s *100 – 30000*	Sets the rate (in seconds) at which the motor torque increases to full when full throttle is applied. Larger values represent slower response.
Accel Release Rate *Accel_Release_Rate_TrqM* `0x3028 0x00`	0.1 – 2.0 s *100 – 2000*	Determines how quickly deceleration will be initiated when the throttle is released while the vehicle is still accelerating. If the release rate is fast (i.e., set to a low value), the transition is initiated abruptly. The transition is smoother if the release rate is set to a higher value (slower transition); however, setting the rate too high can cause the vehicle to feel uncontrollable when the throttle is released, as it will continue to drive for a short time.
Brake Rate *Brake_Rate_TrqM* `0x3029 0x00`	0.1 – 5.0 s *100 – 5000*	Adjusts the rate (in seconds) at which braking torque builds as the vehicle transitions from drive to braking when direction is reversed, the brake pedal is applied, or neutral braking begins. Lower values represent faster times and therefore faster braking; gentler braking is achieved by setting the braking rate to a higher value.
Brake Release Rate *Brake_Release_Rate_TrqM* `0x3831 0x00`	0.1 – 2.0 s *100 – 2000*	Adjusts the rate (in seconds) at which braking torque releases as as the vehicle transitions from braking to drive.
Neutral Braking *Neutral_Braking_TrqM* `0x302E 0x00`	0 – 100% *0 – 32767*	Neutral braking occurs progressively when the throttle is reduced toward the neutral position or when no direction is selected. The neutral braking parameter is adjustable from 0 to 100% of the regen current limit (see Current Limits menu, page 43).
Neutral Taper Speed *Neutral_Taper_Speed_TrqM* `0x302F 0x00`	200 – 6000 rpm *200 – 6000*	Determines the motor speed below which neutral braking current is adjusted when throttle is reduced; see Figure 9. The neutral braking current is linearly reduced by the product of the parameters, Neutral Braking x Regen Current Limit, at the Neutral Taper Speed to the Creep Torque current at zero rpm motor speed. NOTE: Setting the taper speed too low may cause oscillations in the motor.
Forward Full Restraint Speed *Forward_Full_Restraint_Speed _TrqM* `0x386D 0x00`	100 – 32000 rpm *100 – 32000*	Sets the speed point at which the full regen current will be applied to restrain the vehicle from rolling forward. Although this speed is never actually reached, it does set the slope of the restraint strength and can be thought of as a gain; see Figure 9. Setting this parameter too low can cause oscillations.
Back Full Restraint Speed *Back_Full_Restraint_Speed_TrqM _TrqM* `0x386E 0x00`	100 – 32000 rpm *100 – 32000*	Sets the speed point at which the full regen current will be applied to restrain the vehicle from rolling in reverse (backward). Although this speed is never actually reached, it does set the slope of the restraint strength and can be thought of as a gain; see Figure 9. Setting this parameter too low can cause oscillations.

2 - TORQUE MODE — FINE TUNING MENU

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Creep Torque *Creep_Torque_TrqM* `0x3071 0x00`	0 – 100% *0 – 32767*	Determines the amount of torque applied to the vehicle at a stop with no throttle input, to emulate the feel of an automatic transmission automobile; see Fig. 9. ***WARNING!*** When interlock is engaged, creep torque allows vehicle propulsion if a direction is selected even though no throttle is applied. Care should be taken when setting up this parameter. If pedal braking is enabled (page 48), creep torque is progressively disabled as brake is applied so as to prevent the motor from driving into the brakes and thus wasting energy. Creep Torque and Neutral Taper Speed interact to create the slope of the torque response as the vehicle approaches zero speed; see Figure 9. If the vehicle oscillates as it coasts down toward zero speed, try lowering Creep Torque or increasing Neutral Taper Speed.
Brake Full Creep Cancel *Brake_Full_Creep_Cancel_TrqM* `0x3837 0x00`	25 – 100% *8192 – 32767*	Determines the amount of brake pedal input that will fully cancel the creep torque. Amount of cancellation is proportional to the brake input.
Creep Build Rate *Creep_Build_Rate_TrqM* `0x3832 0x00`	0.1 – 5.0 s *100 – 5000*	Determines how fast the programmed creep torque builds when a direction is selected.
Creep Release Rate *Creep_Release_Rate_TrqM* `0x3833 0x00`	0.1 – 5.0 s *100 – 5000*	Determines how fast the programmed creep torque releases when the brake is cancelling the creep torque or when the direction switches are cleared (neutral).
Gear Soften *Gear_Soften_TrqM* `0x302A 0x00`	0 – 100% *0 – 5000*	Adjusts the throttle take-up from linear (0% setting) to an S curve. Larger values create softer throttle take-up, in forward and reverse. Softening is progressively reduced at higher speeds; see Figure 10.
Brake Taper Speed *Brake_Taper_Speed_TrqM* `0x300F 0x00`	200 – 6000 rpm *200 – 6000*	Determines the motor speed below which the maximum braking current is linearly reduced from 100% to 0% at zero speed; see Figure 11. Setting the taper speed too low for the braking current will cause oscillations in the motor as it attempts to brake the vehicle to a stop on very steep slopes. Taper speed is applicable only in response to brake pedal input; it does not affect direction reversal braking or neutral braking. If the vehicle is in restraint when the brake is pressed, the applied braking torque is affected by both Brake Taper Speed and Forward (or Back) Full Restraint Speed. If the vehicle oscillates in this mode, it may be necessary to increase one or more of these parameters.
Reversal Soften *Reversal_Soften* `0x3074 0x00`	0 – 100% *0 – 3000*	Larger values create a softer reversal from regen braking to drive when near zero speed. This helps soften the transition when the regen and drive current limits are set to different values Note: This parameter is not mode-specific and appears in two places. Changing the value of this torque-mode parameter affects the parameter listed in: Program » Speed Mode » Response » Fine Tuning » Reversal Soften.
Max Speed Decel *Max_Speed_Decel_TrqM* `0x3835 0x00`	0.1 – 30.0 s *100 – 30000*	In some applications, the Max Speed value is changed frequently, through VCL or over the CANbus. The Max Speed Decel parameter controls the rate at which the maximum speed setpoint is allowed to change when the value of Max Speed is lowered. The rate set by this parameter is the time to ramp from Typical Max Speed rpm to 0 rpm. For example, suppose you change Max Speed from 3000 rpm to 1000 rpm. If Typical Max Speed is 5000 rpm, and the rate is 5.0 seconds, it will take 5.0 X (3000–1000) ÷ 5000 = 2.0 seconds to ramp from 3000 rpm to 1000 rpm.



In torque mode, the throttle command continuously interpolates between the Throttle=0% and Throttle=100% curves to produce the torque command.

Figure 9

Throttle mapping (torque control mode).

Figure 10

Effect of Gear Soften parameter (torque control mode).

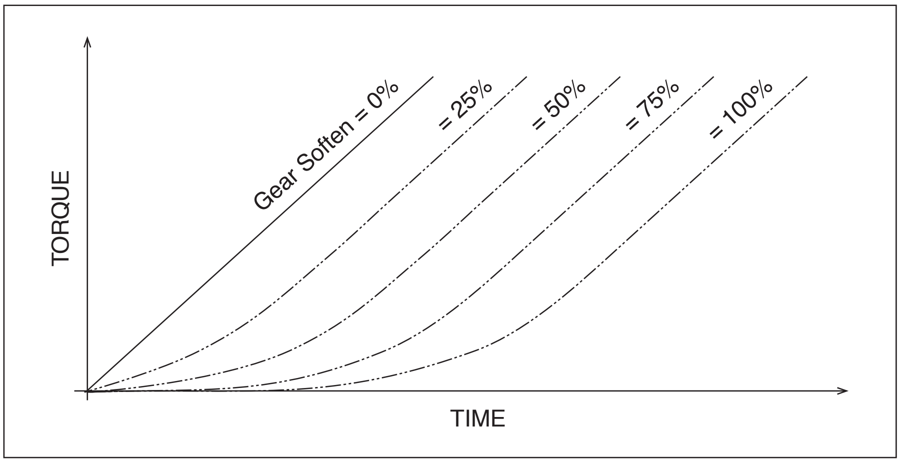
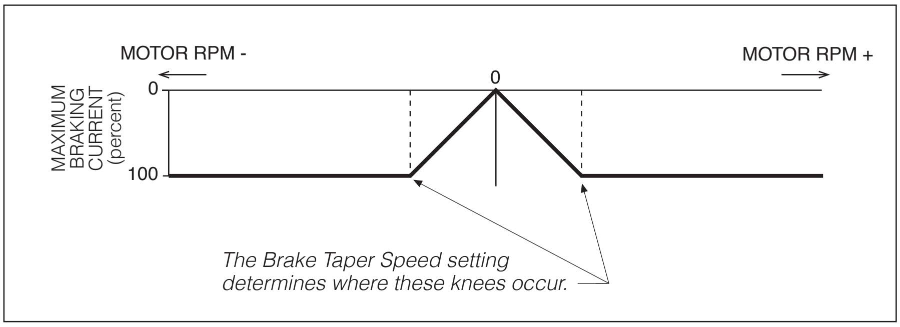


Figure 11

Effect of Brake Taper Speed parameter (torque control mode).



The Brake Taper Speed setting determines where these knees occur.

CURRENT LIMITS MENU

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Drive Current Limit *Drive_Current_Limit* `0x305B 0x00`	5 – 100% *1638 – 32767*	Sets the maximum RMS current the controller will supply to the motor during drive operation, as a percentage of the controller's full rated current.* Reducing this value will reduce the maximum drive torque. **NOTE: Changing this parameter requires the re-setting of the ACIM FW Base Speed parameter** (page 56)**.**
Regen Current Limit *Regen_Current_Limit* `0x305C 0x00`	5 – 100% *1638 – 32767*	Sets the maximum RMS regen current, as a percentage of the controller's full rated current.* The regen current limit applies during neutral braking, direction reversal braking, and speed limiting when traveling downhill.
Brake Current Limit *Brake_Current_Limit* `0x305D 0x00`	5 – 100% *1638 – 32767*	Sets the maximum RMS regen current during braking when a brake command is given, as a percentage of the controller's full rated current.* Typically the brake current limit is set equal to the regen current limit. The brake current limit overrides the regen current limit when the brake input is active.
EMR Current Limit *EMR_Current_Limit* `0x3037 0x00`	5 – 100% *1638 – 32767*	Sets the maximum RMS current allowed for braking and drive when in emergency reverse. The emergency reverse current limit is a percentage of the controller's full rated current.*
Interlock Brake Current Limit *Interlock_Brake_Current_Limit* `0x309D 0x00`	5 – 100% *1638 – 32767*	Sets the maximum RMS regen current during interlock braking, as a percentage of the controller's full rated current.*

** The full rated current depends on the controller model; see specifications in Table D-1 for the rated current of your model.*

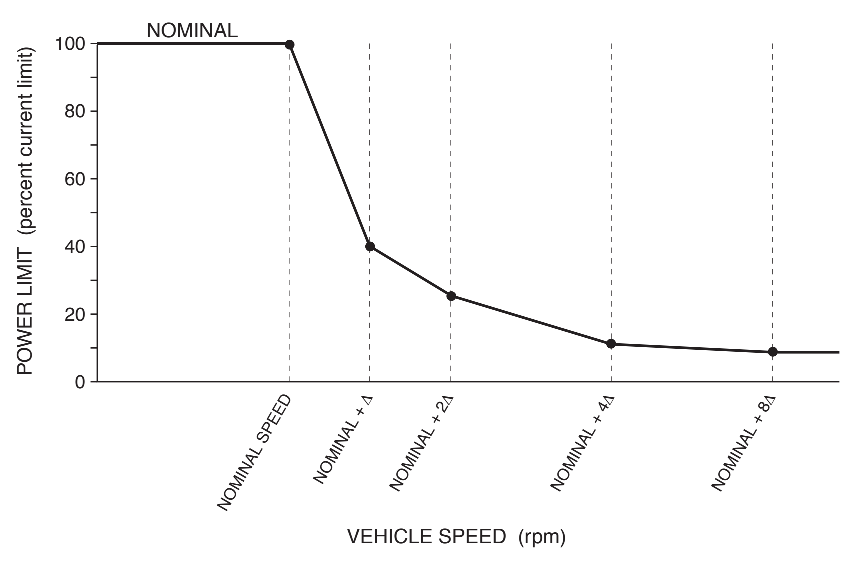
POWER LIMITING MAP MENU

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
PL Nominal Speed *PL_Nominal_Speed* `0x305E 0x00`	100 – 4000 rpm *100 – 4000*	Sets the base speed that will be used in the drive limiting map and regen limiting map. **NOTE: Changing this parameter requires the re-setting of the ACIM FW Base Speed parameter** (page 56)**.**
Delta Speed *PL_Delta_Speed* `0x305F 0x00`	50 – 1000 rpm *50 – 1000*	Sets the width of the delta increment that will be used in the drive limiting map and regen limiting map.

DRIVE LIMITING MAP MENU

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Nominal *PL_Drive_Nominal* `0x3060 0x00`	0 – 100% *0 – 32767*	These parameters define the percentage of drive current limit that will be applied at the speeds defined by the nominal speed and delta speed parameters. The resulting map allows the controller to reduce the drive current as a function of speed. Reducing the power requirements at certain speeds restricts performance. This can be useful for reducing motor heating. It can also be used to keep consistent vehicle power with changing battery state-of-charge. Figure 12 illustrates these parameters' typical usage.
Plus Delta *PL_Drive_Nominal_Plus_Delta* `0x3061 0x00`	0 – 100% *0 – 32767*	
Plus 2xDelta *PL_Drive_Nominal_Plus_2xDelta* `0x3062 0x00`	0 – 100% *0 – 32767*	
Plus 4xDelta *PL_Drive_Nominal_Plus_4xDelta* `0x3063 0x00`	0 – 100% *0 – 32767*	
Plus 8xDelta *PL_Drive_Nominal_Plus_8xDelta* `0x3064 0x00`	0 – 100% *0 – 32767*	

Figure 12



Drive current limiting map (typical example).

REGEN LIMITING MAP MENU

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Nominal *PL_Regen_Nominal* `0x3065 0x00`	0 – 100% *0 – 32767*	These parameters define the percentage of regen current limit or braking current limit that will be applied at the speeds defined by the nominal speed and delta speed parameters. The curve can be shaped to limit the available torque at various speeds. One possible use is to compensate for the torque-speed characteristic of the motor. Figure 13 illustrates two typical usages of these parameters.
Plus Delta *PL_Regen_Nominal_Plus_Delta* `0x3066 0x00`	0 – 100% *0 – 32767*	
Plus 2xDelta *PL_Regen_Nominal_Plus_2xDelta* `0x3067 0x00`	0 – 100% *0 – 32767*	
Plus 4xDelta *PL_Regen_Nominal_Plus_4xDelta* `0x3068 0x00`	0 – 100% *0 – 32767*	
Plus 8xDelta *PL_Regen_Nominal_Plus_8xDelta* `0x3069 0x00`	0 – 100% 0 – 32767	

Figure 13

Regen current limiting map (two examples).

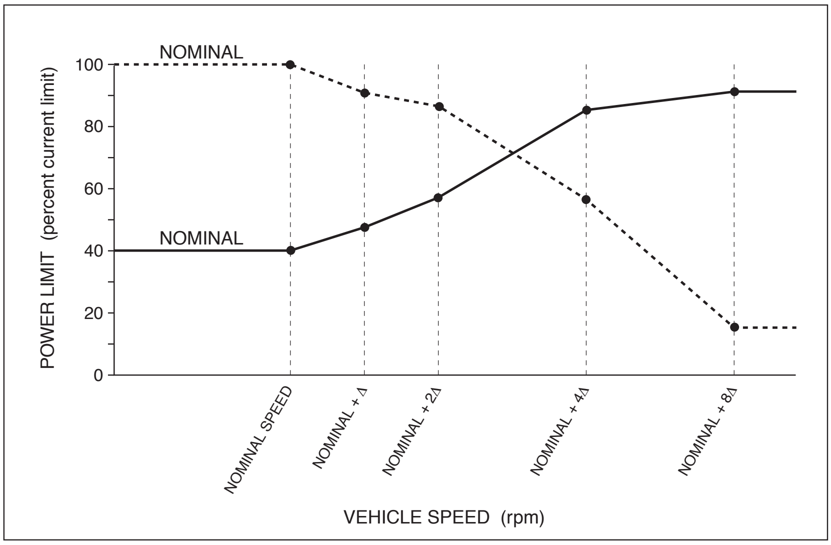


Figure 14

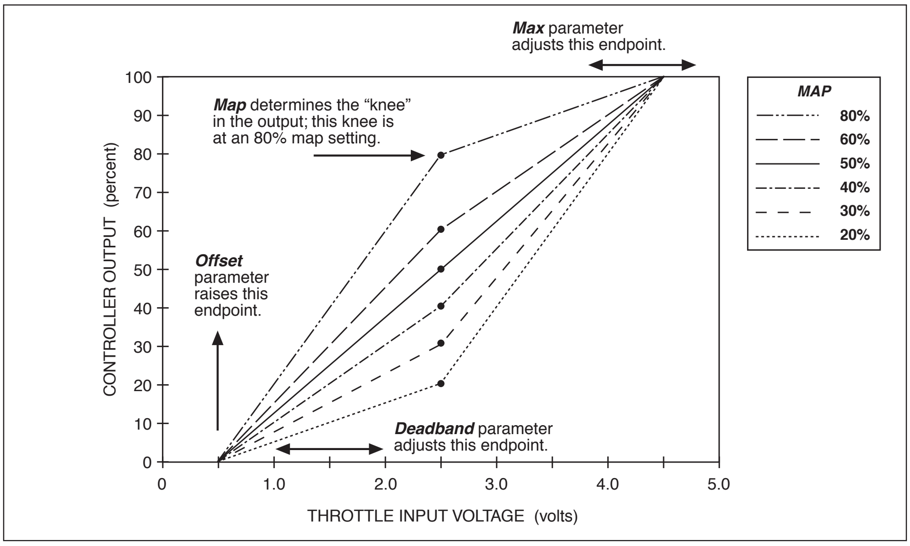
Effect of throttle adjustment parameters. Together these four generic parameters determine the controller's response to throttle demand (in forward or reverse) and to brake demand.

In the examples shown in this figure,

Deadband = 0.5 V

Max = 4.5 V

Offset = 0.



THROTTLE MENU

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Throttle Type **PCF** *Throttle_Type* `0x3000 0x00`	1 – 5 *1 – 5*	These E and SE controllers accept a variety of throttle inputs. The throttle type parameter can be programmed as follows: 1. 2-wire rheostat, 5 kΩ–0 input 2. single-ended 3-wire 1 kΩ–10 kΩ potentiometer, or 0–5 V voltage source 3. 2-wire rheostat, 0–5 kΩ input 4. wigwag 3-wire 1 kΩ–10 kΩ potentiometer, or 0–5 V voltage source 5. VCL input (*VCL_Throttle*) **NOTE:** Do not change this parameter while the controller is powering the motor. Any time this parameter is changed a Parameter Change Fault (fault code 49) is set and must be cleared by cycling power; this protects the controller and the operator.
Forward Deadband *Forward_Deadband* `0x3001 0x00`	0.00 – 5.00 V *0 – 32767*	Defines the wiper voltage at the throttle deadband threshold. Increasing the throttle deadband setting will increase the neutral range. This parameter is especially useful with throttle assemblies that do not reliably return to a well-defined neutral point, because it allows the deadband to be defined wide enough to ensure that the controller goes into neutral when the throttle mechanism is released.
Forward Map *Forward_Map* `0x3002 0x00`	0 – 100% *0 – 32767*	Modifies the vehicle's response to the throttle input. Setting the throttle map at 50% provides a linear output response to throttle position. Values below 50% reduce the controller output at low throttle settings, providing enhanced slow speed maneuverability. Values above 50% give the vehicle a faster, more responsive feel at low throttle settings. The map value is the percentage of controller output at half throttle [(deadband + max)/2].
Forward Max *Forward_Max* `0x3003 0x00`	0.00 – 5.00 V *0 – 32767*	Defines the wiper voltage required to produce 100% controller output. Decreasing the throttle max setting reduces the wiper voltage and therefore the full stroke necessary to produce full controller output. This parameter allows reduced-range throttle assemblies to be accommodated
Forward Offset *Forward_Offset* `0x3004 0x00`	0 – 100% *0 – 32767*	Defines the initial controller output generated when the throttle is first rotated out of the neutral deadband. For most vehicles, a setting of 0 is appropriate. For heavy vehicles, however, increasing the offset may improve controllability by reducing the amount of throttle required to start the vehicle moving.
Reverse Deadband *Reverse_Deadband* `0x3005 0x00`	0.00 – 5.00 V *0 – 32767*	The four Throttle Reverse parameters are the same as their Throttle Forward counterparts, and apply when the throttle direction is reversed.
Reverse Map *Reverse_Map* `0x3006 0x00`	0 – 100% *0 – 32767*	
Reverse Max *Reverse_Max* `0x3007 0x00`	0.00 – 5.00 V *0 – 32767*	
Reverse Offset *Reverse_Offset* `0x3008 0x00`	0 – 100% *0 – 32767*	
Throttle Filter *Throttle_Filter* `0x3030 0x00`	0.5 – 125.0 Hz 131 – 32767	Sets the low pass filter cutoff frequency for the throttle pot wiper input. Higher values will make the throttle more responsive to quick changes. Lower values will make the throttle less responsive to electrical noise.

NOTE: All four throttle adjustment parameters — Deadband, Map, Max, Offset — condition the raw throttle voltage into a single % throttle command, as shown in Figure 14 on the previous page.

THROTTLE MENU, cont'd

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
HPD SRO Type **PCF** *HPD_SRO_Type* `0x30CF 0x00`	0 – 3 *0 – 3*	Determines the type of HPD (High Pedal Disable) / SRO (Static Return to Off) protection. One type of checks is available for material-handling vehicles, and two types for golf-style vehicles. If any of the HPD/SRO checks finds an input sequencing problem, an HPD/Sequencing Fault (flash code 47) is set. 0. HPD/SRO feature is disabled. 1. HPD/SRO enabled for material-handling vehicles. ***HPD:*** If throttle input is received before interlock input. ***SRO:*** If direction input is received before interlock input. The HPD/SRO check is made when the interlock input changes from Off to On. If the throttle input >25% or a direction input is On, an HPD/Sequencing Fault is set. The HPD/Sequencing Fault is cleared by returning the throttle input to <25% or the direction inputs to Off. 2. Golf-style HPD that allows direction reversal while driving. ***HPD:*** Throttle input received before interlock, or throttle input received before direction input while vehicle is stationary. ***SRO:*** None. The HPD check is made when the interlock input or direction inputs are Off and the vehicle is stationary. If the throttle input >25%, an HPD/Sequencing Fault is set. No SRO check is made with this type, so the order of the interlock and direction inputs does not matter. The HPD/Sequencing Fault is cleared by returning the throttle input to <25% or the direction inputs to Off. 3. Golf-style HPD that prevents direction reversal while driving. ***HPD:*** If throttle input is received before interlock or direction input. ***SRO:*** None. HPD check is made when the interlock input or direction inputs are Off. If the throttle input >25%, an HPD/Sequencing Fault is set. The check is done regardless of vehicle speed, so reversing direction with throttle input >25% will result in a fault. No SRO check is made with this type, so the order of the interlock and direction inputs does not matter The HPD/Sequencing Fault is cleared by returning the throttle input to <25% or the direction inputs to Off.
Sequencing Delay *Sequencing_Delay* `0x3009 0x00`	0.0 – 5.0 s *0 – 1250*	Typically the sequencing delay feature allows the interlock switch to be cycled within a set time (the defined sequencing delay), thus preventing inadvertent activation of HPD/SRO. This feature is especially useful in applications where the interlock switch may bounce or be momentarily cycled during operation.
VCL Throttle Enable |*VCL_Throttle_Enable* |*VCL_Throttle_Enable_Bit0* **[Bit 0]** `0x3099 0x00`	On / Off *On / Off*	When programmed On, the throttle processing with fault detection will operate normally; however, the throttle command will require VCL to define the connection between the OS_Throttle and VCL_Throttle variables. This allows VCL flexibility and customization of throttle processing, while still allowing Throttle_Type 1–4 with throttle fault detection. Figure 15 (page 105) illustrates these throttle chains.

BRAKE MENU

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Brake Pedal Enable *Brake_Pedal_Enable* *OptionBits1* **[Bit 3]** `0x306A 0x00`	On / Off *On / Off*	Determines whether the brake input and algorithm are enabled, making the brake throttle part of the motor control command.
Brake Type **PCF** *Brake_Type* `0x300A 0x00`	1 – 5 *1 – 5*	These E and SE controllers accept a variety of brake inputs. The brake type parameter can be programmed as follows: 1. 2-wire rheostat, 5 kΩ–0 input 2. Single-ended 3-wire 1 kΩ–10 kΩ potentiometer, 0–5 V voltage source 3. 2-wire rheostat, 0–5 kΩ input 4. (not applicable) 5. VCL input (*VCL_Brake*) NOTE: Do not change this parameter while the controller is powering the motor. Any time this parameter is changed a Parameter Change Fault (fault code 49) is set and must be cleared by cycling power; this protects the controller and the operator.
Brake Deadband *Brake_Deadband* `0x300B 0x00`	0.00 – 5.00 V *0 – 32767*	The four Brake throttle adjustment parameters are the same as their Drive throttle counterparts; see descriptions and Figure 14.
Brake Map *Brake_Map* `0x300C 0x00`	0 – 100% *0 – 32767*	
Brake Max *Brake_Max* `0x300D 0x00`	0.00 – 5.00 V *0 – 32767*	
Brake Offset *Brake_Offset* `0x300E 0x00`	0 – 100% *0 – 32767*	
Brake Filter *Brake_Filter* `0x3031 0x00`	0.5 – 125.0 Hz *131 – 32767*	Sets the low pass filter cutoff frequency for the pot2 wiper input. Higher values will make the brake more responsive to quick changes. Lower values will make the brake less responsive to electrical noise.
VCL Brake Enable *VCL_Brake_Enable* *VCL_Brake_Enable_Bit0* **[Bit 0]** `0x301E 0x00`	On / Off *On / Off*	When programmed On, the brake processing with fault detection will operate normally; however, the brake command will require VCL to define the connection between the OS_Brake and VCL_Brake variables. This allows VCL flexibility and customization of throttle processing, while still allowing Brake_Type 1–3 with brake fault detection. Figure 15 (page 105) illustrates these brake chains.

EM BRAKE CONTROL MENU

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Brake Type **PCF** *EM_Brake_Type* `0x3097 0x00`	0 – 2 *0 – 2*	This brake type parameter determines how the EM brake responds to the interlock input, throttle, and vehicle motor speed. 0. EM brake function disabled. The EM brake driver (PWM2) is released to general I/O use with VCL. 1. EM brake controlled by interlock. The controller will command the EM brake to release whenever the interlock is closed (Interlock = On). If interlock braking is enabled and the interlock opens when the vehicle is moving at motor speed greater than Set_Speed_Threshold, the controller will brake the vehicle to a stop (with interlock braking) and then command the EM brake to set. If the vehicle motor speed is less than this threshold, the EM brake will engage after the Sequencing_Delay has expired. If interlock braking is disabled, the EM brake will engage after the Sequencing_Delay has expired. 2. EM brake controlled by interlock and neutral. The controller will command the EM brake to set whenever the throttle command is zero and motor speed is less than Set_Speed_Threshold. Position Hold will be enabled automatically.
Pull In Voltage *EM_Brake_Pull_In_Voltage* `0x3072 0x00`	0 – 100% *0 – 32767*	The EM brake pull-in voltage allows a high initial voltage when the EM brake first turns on, to ensure brake release. After 1 second, this peak voltage drops to the EM brake holding voltage. Note: The Battery Voltage Compensated parameter controls whether the pull-in and holding voltages are battery voltage compensated.
Holding Voltage *EM_Brake_Holding_Voltage* `0x3098 0x00`	0 – 100% *0 – 32767*	The EM brake holding voltage allows a reduced average voltage to be applied to the brake coil once the brake has been released. This parameter must be set high enough to hold the brake released under all shock and vibration conditions the vehicle will be subjected to. Note: The Battery Voltage Compensated parameter controls whether the pull-in and holding voltages are battery voltage compensated.
Battery Voltage Compensated |*EM_Brake_Battery_Voltage_Compensated* |*EM_Brake_Battery_Voltage_Compensated_Bit0* **[Bit 0]** `0x302D 0x00`	On / Off *On / Off*	This parameter determines whether the EM brake pull-in and holding voltages are battery voltage compensated. When set On, the pull-in and holding voltages are compensated relative to the set Nominal Voltage (see Battery Menu, page 62). In other words, the output voltage is adjusted to compensate for swings in battery voltage, so the percentage is relative to the set Nominal Voltage—not to the actual voltage. For example, suppose Nominal Voltage is set to 48V and Holding Voltage is set to 75% (36V) to the output driver. Now suppose the bus voltage dips to 40V. If Battery Voltage Compensated = On, the output will still be 36V (Nominal Voltage × Holding Voltage) to the coil. If Battery Voltage Compensated = Off, the output will be 30V (Actual Voltage × Holding Voltage) to the coil.
Set EM Brake On Fault |*EM_Brake_Set_Upon_Fault* |*EM_Brake_Set_Upon_Fault_Bit0* **[Bit 0]** `0x309B 0x00`	On / Off *On / Off*	When programmed On, the controller's operating system will set the electromagnetic brake when a fault occurs that has a fault action of ShutdownEMBrake. See the Troubleshooting Chart, Chapter 10, for a list of all the faults that have a fault action of ShutdownEMBrake.
Zero Speed Threshold *Zero_Speed_Threshold* `0x306F 0x00`	5 – 100 rpm *5 – 100*	Determines the speed below which the EM brake will be commanded to set. Setting this speed too high may cause a jerky stop when the EM brake sets and stops the motor. This parameter appears twice in the menu structure. Changing the value of this parameter affects this (same) parameter in the Position Hold menu, page 38. ***This parameter is re-named for os31. It is the same as the previous Set Speed Threshold parameter.***
Zero Speed Threshold Time *Zero_Speed_Threshold_Time* `0x30DA 0x00`	0 – 480 ms *0 – 60*	Determines how long motor speed must be below Zero_Speed_Threshold to declare zero speed. This parameter appears twice in the menu structure. Changing the value of this parameter affects this (same) parameter in the Position Hold menu, page 38. ***This is a new parameter for os31***

EM BRAKE CONTROL MENU, cont'd

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Position Hold Settling Time *Position_Hold_Settling_Time* `0x3024 0x00`	0 – 5000 ms *0 – 156*	Determines how long the position hold function is allowed to operate before the EM brake is set. This time should be set long enough for the position hold to settle. This parameter appears twice in the menu structure. Changing the value of this parameter affects this (same) parameter in the Position Hold menu, page 38. ***This parameter is re-named for os31. It is the same as the previous Set Speed Settling Time parameter.*** NOTE *
Brake Set Time *EM_Brake_Set_Time* `0x30DB 0x00`	40 – 2000 ms *5 – 250*	Estimated time for the EM brake to physically set after the holding voltage is released. This determines how long the controller waits, after removing voltage from the brake, before released the torque. This should be set longer than the actual brake setting time to ensure the vehicle doesn't move before the brake fully engages. ***This is a new parameter for os31.***
Torque Release Time *EM_Brake_Torque_Release_Time* `0x30DC 0x00`	40 – 2000 ms *5 – 250*	Time to release torque after EM Brake has set and motor has stopped (EMBrakeEngagedAndStopped state). ***This is a new parameter for os31.***
Brake Release Time *EM_Brake_Release_Time* `0x3073 0x00`	40 – 2000 ms *5 – 250*	Estimated time for the EM brake to physically release after the pull-in voltage is applied. This is used to ensure the position hold torque buildup is complete before the brake releases. When set too low, the vehicle may experience rollback on EM brake release. ***This parameter is re-named for os31. It is the same as the previous Release Delay parameter***
Torque Preload Time *EM_Brake_Torque_Preload_Time* `0x3090 0x00`	0 – 800 ms *0 – 100*	Estimated worst-case time to build up the torque required to hold the vehicle stationary on a hill prior to EM brake release. This is used in conjunction with Release Delay to determine when to release the brake and allow the speed request to slew away from zero. ***This parameter is re-named for os31. It is the same as the previous Torque Preload Delay parameter*** NOTE *
Torque Preload Enable |*EM_Brake_Torque_Preload_Enable* |*EM_Brake_Torque_Preload_Enable_Bit0* **[Bit 0]** `0x389D 0x00`	On / Off *On / Off*	When enabled, this function eliminates rollback when the throttle is re-engaged on a ramp by forcing the vehicle to first enter position-hold before setting the EM brake, and then "remembering" the amount of torque that was necessary to hold it on the ramp. When throttle is re-engaged, this value is loaded in the motor before the EM brake is released. The torque value is cleared automatically when KSI power is cycled. Off = When a valid throttle input is received, the speed controller will start with no torque preload as soon as the Release Delay expires. This will allow some rollback when the EM brake releases. This rollback can be reduced by raising the Exit Rollback Reduction parameter in the Position Hold Menu (page 38). On = When a valid throttle input is received, the speed controller will start with a pre-set torque as measured by position-hold when the vehicle came to a stop. NOTE *
Save Torque Preload |*Save_Torque_Preload* |*Save_Torque_Preload_Bit0* **[Bit 0]** `0x38C9 0x00`	On/Off *On/Off*	This parameter controls whether the EM Brake torque preload is saved over a keyswitch cycle. If Torque_Preload_Cancel_Delay is nonzero and this parameter = On, the timer starts again upon startup (KSI cycle) such that the countdown is from the full value of the Torque_Preload_Cancel_Delay parameter. ***This is a new parameter for os31.***

NOTE: **This parameter is applicable only when Speed Mode or Speed Mode Express is selected and either Position Hold Enable = On or EM Brake Type = 2.*

EM BRAKE CONTROL MENU, cont'd

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Torque Preload Cancel Delay *EM_Brake_Torque_Preload_ Cancel_Delay* `0x3091 0x00`	0 – 120 s *0 – 15000*	The timer starts after the EM brake is set. If the timer expires before the throttle is re-engaged, the torque preload memory will be cleared. Setting this parameter to zero disables the timer, i.e., the preload is never cancelled. The purpose of this delay is to prevent the vehicle from lunging forward if it is unloaded on a hill such that the torque measured by position-hold is no longer valid. NOTE: This parameter is applicable only when Torque Preload Enable = On (see parameter, previous page).
EM Brake Fault Motor Revs *EM_Brake_Fault_Motor_Revs* `0x3894 0x00`	1.0 – 20.0 *10 – 200*	Defines the allowable number of motor revolutions after the EM brake is set before an EM Brake Failed to Set fault is issued (fault code 92).

DRIVERS: MAIN CONTACTOR MENU

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Main Enable |*Main_Enable* |*OptionBits1* **[Bit 0]** `0x306A 0x00`	On / Off *On / Off*	When programmed On, the controller's native software controls the main contactor when the interlock is enabled; when programmed Off, the contactor is controlled by VCL. **NOTE: With Main Enable programmed Off, the controller will not be able to open the main contactor in serious fault conditions and the system will therefore not meet EEC safety requirements.**
Main Interlock Type *Main_Interlock_Type* `0x386F 0x00`	0 – 1 *0 – 1*	When set to 0, the main contactor and interlock each work as determined by their respective parameters. When set to 1, the main contactor will pull in with KSI (like a Type 2 interlock) but the interlock input (pin 9, Switch 3) enables/disables drive and engages interlock braking (like a Type 0 or Type 1 interlock).
Pull In Voltage *Main_Pull_In_Voltage* `0x303C 0x00`	0 – 100% *0 – 32767*	The main contactor pull-in voltage parameter allows a high initial voltage when the main contactor driver first turns on, to ensure contactor closure. After 1 second, this peak voltage drops to the contactor holding voltage. NOTE: The Battery Voltage Compensated parameter (below) controls whether the pull-in and holding voltages are battery voltage compensated.
Holding Voltage *Main_Holding_Voltage* `0x303D 0x00`	0 – 100% *0 – 32767*	The main contactor holding voltage parameter allows a reduced average voltage to be applied to the contactor coil once it has closed. This parameter must be set high enough to hold the contactor closed under all shock and vibration conditions the vehicle will be subjected to. NOTE: The Battery Voltage Compensated parameter (below) controls whether the pull-in and holding voltages are battery voltage compensated.

DRIVERS: MAIN CONTACTOR MENU, cont'd

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Battery Voltage Compensated *Main_Driver_Battery_Voltage_Compensated* *Main_Driver_Battery_Voltage_Compensated_Bit0* **[Bit 0]** `0x302C 0x00`	On / Off *On / Off*	This parameter determines whether the main pull-in and holding voltages are battery voltage compensated. When set On, the pull-in and holding voltages are set relative to the set Nominal Voltage (see Battery Menu, page 62). In other words, the output voltage is adjusted to compensate for swings in battery voltage, so the percentage is relative to the set Nominal Voltage—not to the actual voltage. For example, suppose Nominal Voltage is set to 48V and Holding Voltage is set to 75% (36V) to the output driver. Now suppose the bus voltage dips to 40V. If Battery Voltage Compensated = On, the output will still be 36V (Nominal Voltage x Holding Voltage) to the coil. If Battery Volt- age Compensated = Off, the output will be 30V (Actual Voltage × Holding Voltage) to the coil.
Interlock Type *Interlock_Type* `0x303E 0x00`	0 – 2 *0 – 2*	Three interlock options are available: 0 = interlock turns on with switch 3. 1 = interlock controlled by VCL functions. 2 = interlock turns on with KSI.
Open Delay *Open_Delay* `0x303F 0x00`	0.0 – 40.0 s *0 – 10000*	Applicable only when Interlock Type = 0 or 1. The delay can be set to allow the contactor to remain closed for a period of time (the delay) after the interlock switch is opened. The delay is useful for preventing unnecessary cycling of the contactor and for maintaining power to auxiliary functions that may be used for a short time after the interlock switch has opened.
Weld Check Enable *Weld_Check_Enable* *OptionBits1* **[Bit 2]** `0x306A 0x00`	On / Off *On / Off*	When programmed On, the controller performs a test to make sure the main contactor is open (not welded shut) before it is commanded to close. This test is not performed if this parameter is Off. The main contactor driver, however, is always protected from short circuits.
Main DNC Check Enable *Main_DNC_Check_Enable* *OptionBits4* **[Bit 7]** `0x306D 0x00`	On / Off *On / Off*	When programmed On, the controller performs a test immediately after the main contactor is commanded to close, to make sure the contactor has in fact closed. The test is not performed if this parameter is programmed Off. The main contactor driver, however, is always protected from short circuits.
Main DNC Runtime Threshold *Main_DNC_Runtime_Threshold* `0x3032 0x00`	0.0 – 200.0 V *0 – 12800*	Sets the threshold used for the ongoing check that ensures the main contactor remains closed while in operation. The Main DNC Runtime Threshold is the maximum voltage difference between the Keyswitch and Capacitor voltages. When the voltage difference is above this threshold, and the battery current is low, a Main Did Not Close fault will be set. Setting this parameter lower will increase the sensitivity of the fault detection. Setting this parameter too low may cause false fault trips due to normal voltage drops between the keyswitch and capacitor voltages. Setting this parameter = 0 V will disable the Main Did Not Close fault check.
Precharge Enable *Precharge_Enable* *OptionBits2* **[Bit 6]** `0x306B 0x00`	On / Off *On / Off*	Turns the precharge feature on and off. Precharge provides a limited current charge of the controller's internal capacitor bank before the main contactor is closed. This decreases the arcing that would otherwise occur when the contactor is closed with the capacitor bank discharged.

DRIVERS: PROPORTIONAL DRIVER MENU

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
PD Enable **PCF** │*PD_Enable* │*OptionBits1* **[Bit 6]** `0x306A 0x00`	On / Off *On / Off*	Determines how the PWM of the proportional driver is controlled. When programmed On, it is controlled by the controller's PD current control software. When programmed Off, it is controlled by the VCL function *Put_PWM* (PWM5, value); see Figure 17, page 109.
Hyd Lower Enable │*Hyd_Lower_Enable* │*OptionBits1* **[Bit 7]** `0x306A 0x00`	On / Off *On / Off*	When programmed On, lowering is controlled by throttle position. When programmed Off, lowering is controlled by the VCL variable *VCL_PD_Throttle*; see Figure 17, page 109.
PD Max Current *PD_Max_Current* `0x3040 0x00`	0.00 – 2.00 A *0 – 607*	*The lift-lowering speed is determined by the aperture of the proportional valve. This parameter sets the maximum allowed current through the valve, which in turn defines its aperture.
PD Min Current *PD_Min_Current* `0x3041 0x00`	0.00 – 2.00 A *0 – 607*	*Sets the minimum allowed current through the proportional valve. Most proportional valves need a non-zero closed current in order to start opening immediately when Lower is requested.
PD Dither % *PD_Dither_Percent* `0x3042 0x00`	0 – 100 % *0 – 32767*	*Dither provides a constantly changing current in the coil to produce a rapid back-and-forth motion of the valve; this keeps the valve lubricated and allows low-friction, precise movement. The PD Dither % parameter specifies the amount of dither as a percentage of the PD max current, and is applied in a continuous cycle of add%-subtract%.
PD Dither Period *PD_Dither_Period* `0x3043 0x00`	16 – 112 ms *1 – 7*	*Sets the period for proportional valve dither.
PD Kp *PD_Kp* `0x3044 0x00`	1 – 100 % *82 – 8192*	*Sets the proportional gain of the current feedback controller. Higher gains force the control loop to respond quickly but may cause oscillations.
PD Ki *PD_Ki* `0x3045 0x00`	1 – 100 % *327 – 32767*	*Sets the integral gain of the current feedback controller. Integral gain tries to force the error to zero. Higher gains force the control loop to respond quickly but may cause oscillations.

**These parameter descriptions assume the proportional driver is being used to drive a proportional valve, and that the PD current control software is active (PD_Enable = On).*

DRIVERS: DRIVER 3 MENU

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Contactor Enable │*Hydraulic_Contactor_Enable* │*OptionBits4* **[Bit 1]** `0x306D 0x00`	On / Off *On / Off*	When programmed On, VCL functions control Driver 3 as the hydraulic pump contactor. On: The VCL function Start_Pump() will close the pump contactor according to the defined pull-in and holding voltages. The VCL function Stop_Pump() will open the pump contactor. Off: Driver 3 will be available for general VCL usage. Start_Pump() and Stop_Pump() will not have any effect.
Pull In Voltage *Driver3_Pull_In_Voltage* `0x3864 0x00`	0 – 100% *0 – 32767*	The pull-in voltage parameter allows a high initial voltage when the contactor driver first turns on, to ensure contactor closure. After 1 second, this peak voltage drops to the contactor holding voltage. NOTE: This voltage will be battery voltage compensated.
Holding Voltage *Driver3_Holding_Voltage* `0x3865 0x00`	0 – 100% *0 – 32767*	The holding voltage parameter allows a reduced average voltage to be applied to the contactor coil once it has closed. This parameter must be set high enough to hold the contactor closed under all shock and vibration conditions the vehicle will be subjected to. NOTE: This voltage will be battery voltage compensated.

DRIVERS: FAULT CHECKING MENU

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Driver1 Checks Enable │*Driver1_Checks_Enable* │*OptionBits2* **[Bit 1]** `0x306B 0x00`	On / Off *On / Off*	The five Checks Enable parameters are used to enable driver and coil fault detection at the five individual drivers (at Pins J1-6, J1-5, J1-4, J1-3, and J1-2). When a Driver Checks parameter is enabled, the associated driver, driver wiring, and driver load are checked to verify that the driver correctly drives the load both high and low. The checks will occur regardless of the PWM output of the driver. The checks will detect both open and shorted conditions. When a fault is detected, the controller opens the driver and issues a fault code. If nothing is connected to a driver, its Checks Enable parameter should be set Off. NOTE: Short circuit protection is always active at these five drivers, regardless of how Checks Enable is set.
Driver2 Checks Enable │*Driver2_Checks_Enable* │*OptionBits2* **[Bit 2]** `0x306B 0x00`	On / Off *On / Off*	
Driver3 Checks Enable │*Driver3_Checks_Enable* │*OptionBits2* **[Bit 3]** `0x306B 0x00`	On / Off *On / Off*	
Driver4 Checks Enable │*Driver4_Checks_Enable* │*OptionBits2* **[Bit 4]** `0x306B 0x00`	On / Off *On / Off*	
PD Checks Enable │*PD_Checks_Enable* │*OptionBits2* **[Bit 5]** `0x306B 0x00`	On / Off *On / Off*	
External Supply Max *External_Supply_Max* `0x3046 0x00`	0 – 200 mA *0 – 800*	Sets the upper threshold of the combined current of the 5V and 12V external supplies. At or above this threshold a fault will be created that can be read by VCL.
External Supply Min *External_Supply_Min* `0x3047 0x00`	0 – 200 mA *0 – 800*	Sets the lower threshold of the combined current of the 5V and 12V external supplies. At or below this threshold a fault will be created that can be read by VCL.

DRIVERS: PWM FREQUENCY PARAMETER

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
PWM Frequency *PWM_Frequency* `0x3938 0x00`	100 – 1000 Hz *100 – 1000*	This single parameter defines the frequency of Drivers 1 through 4.

MOTOR MENU

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Typical Max Speed *Typical_Max_Speed* `0x304D 0x00`	500 – 8000 rpm *500 – 8000*	Set this parameter to the typical maximum motor speed of the vehicle. This value does not need to be set precisely; an estimate will do. All of the vehicle response rates are normalized to Typical Max Speed. For example, suppose Typical_Max_Speed is fixed at 6000 rpm, and Full_Accel_Rate_LS_SpdM = 3.0 seconds: If Max_Speed_SpdM = 6000 rpm, it will take 3.0 seconds to accelerate from zero to top speed (6000 rpm). If Max_Speed_SpdM = 3000 rpm, it will take 1.5 seconds to accelerate from zero to top speed (3000 rpm). If Max_Speed_SpdM = 1000 rpm, it will take 0.5 seconds to accelerate to accelerate from zero to top speed (1000 rpm)

MOTOR: CONTROL ALGORITHMS MENU

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Motor Technology *Motor_Technology* `0x3814 0x00`	0 – 1 *0 – 1*	Set this parameter to the type of motor in your vehicle: 0 = ACIM (Induction Motor) 1 = SPM (Surface PM Motor). NOTE: A Parameter Mismatch Fault will result unless the Feedback Type (page 59) matches the Motor Technology setting: If Motor Technology = 0 (ACIM), then Feedback Type must = 1 (quadrature encoder). If Motor Technology = 1 (SPM), then Feedback Type must = 2 (Sin/Cos sensor).

MOTOR: 0 – ACIM: CHARACTERIZATION TESTS MENU

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Test Enable *IM_AutoChar_Test_Enable* `0x3800 0x00`	0 – 1 *0 – 1*	Enables ACIM (induction motor) characterization with quadrature encoder to begin once Test Throttle is asserted. See Chapter 8A for the complete description of the ACIM motor characterization procedure.
Test Throttle *IM_Test_Throttle* `0x3034 0x00`	–1 – 1 *–1 – 1*	Begins ACIM characterization if the Test Enable is asserted. This parameter is also used to change the direction of the motor to the forward direction during ACIM motor characterization. **Important:** If the motor starts to turn in the **positive-rpm** vehicle speed direction, set Test Throttle = **1**. If it turns in the **negative-rpm** direction, set Test Throttle = **–1**. See Chapter 8A for the complete description of the ACIM motor characterization procedure.
Motor Poles *IM_MotorData6* `0x3805 0x00`	2 – 8 *1 – 4*	This parameter is used to select the number of poles before beginning the ACIM motor characterization procedure. See Chapter 8A for the complete description of the ACIM motor characterization procedure and how this parameter is used.
Max Test Speed *IM_AutoChar_Max_Test_Speed* `0x38A0 0x00`	500 – 8000 rpm *500 – 8000*	This parameter is used to set the maximum motor speed allowed during ACIM motor characterization. See Chapter 8A for the complete description of the ACIM motor characterization procedure and how this parameter is used.
Max Test Current *IM_AutoChar_Max_Test_Current* `0x38A1 0x00`	10 – 100% *3277 – 32767*	This parameter is used to set the maximum motor current allowed during ACIM motor characterization. See Chapter 8A for the complete description of the ACIM motor characterization procedure and how this parameter is used.
SlipGain *IM_MotorData8* `0x3819 0x00`	0.00 – 200.00 *0 – 20000*	This parameter is adjusted during ACIM motor characterization to tune the motor to deliver the maximum torque per amp. See Chapter 8A for the complete description of the ACIM motor characterization procedure and how this parameter is used.
Current Reg Tuning Test Enable *IM_CR_Tuning_Test_Enable* `0x388B 0x00`	0 – 1 *0 – 1*	This parameter is typically applicable for previously auto-characterized (Type 0) induction motors. It performs only the current regulation tuning portion of the motor characterization on existing Type 0 motors (e.g., prior to os26/30). To begin, clear any existing faults, then set the Interlock = On and this parameter = 1. Similar to the auto-characterization routine steps in Chapter 8A, then set Test Enable = 1 followed by setting Test Throttle = 1. The controller will run the tuning test and issue a Parameter Change Fault when finished. If a new (or existing Type 0) motor is auto-characterized following the steps in Chapter 8A, do not use this parameter, as it is automatically included in the full auto-characterization routine. Consult your Curtis distributor or support engineer for further assistance based on your motor and its application.

Quick Links:
Chapter 8A (ACIM motor characterization) p.85

MOTOR: 0 – ACIM: FIELD WEAKENING CONTROL MENU

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
FW Base Speed *FW_Base_Speed* `0x3857 0x00`	200 – 12000 rpm *200 – 12000*	Sets the speed at which modulation depth has reached 100% (all available voltage is used) and where field weakening begins. This parameter is scaled by an internal motor characterization parameter, so the setting of FW Base Speed should always be done using the tuning test, which will take into account the scaling factor. Entering a speed observed from a torque vs. speed plot should not be done, as this number fails to take into account the internal scaling factor. **This parameter needs to be set during initial setup (chapter 7) and reset each time the Motor Type or the low speed current limit is changed.** For example, if the Drive_Current_Limit (page 43) or PL_Drive_Nominal (page 44) parameters are lowered, reset this FW Base Speed parameter. To determine the correct value, perform this “base speed” tuning test. The test should be run with batteries that have a reasonable charge. In either Speed Mode or Torque Mode, set their accel rates to be fast—so the motor will be accelerating at full current during the test. Next, set this FW Base Speed parameter to 6000 rpm (i.e., at a high-enough speed that its value will not interfere with the test result). From a stop, apply full throttle and accelerate to a high-speed beyond the expected base speed. After the motor settles at this speed for a moment, release the throttle to stop the test. Note the value displayed in Monitor » Controller » Motor Tuning » Base Speed Captured (page 76), and enter this value for this FW Base Speed parameter setting. For traction motors, the test restarts each time the vehicle comes to a stop and the throttle is released, so be sure to note the Base Speed Captured value before driving away. For pump motors, follow the instructions in Chapter 8A, Part 2b.
Field Weakening Drive *Field_Weakening_Drive* `0x3033 0x00`	0 – 100% *0 – 1024*	Sets the amount of field weakening allowed while driving the motor. Field Weakening Drive will affect efficiency and torque only at speeds above the programmed FW Base Speed. Low settings will result in better efficiency but less torque; higher settings will result in more torque and less efficiency. A setting of zero will disable field weakening, thus resulting in the highest efficiency and lowest torque above base speed. To keep motor and controller heating to a minimum (high efficiency), Field Weakening Drive should be set just high enough to meet the high speed performance specifications. (Typical high speed performance specifications are maximum drive speed with full load, or maximum lift speed with full load.) The drive current limiting map (Fig. 12, page 44) can also be used to restrict performance at all speeds. The maximum setting of the Field Weakening Drive parameter depends on the type of motor characterization that was used. *If the ACIM motor was dyno characterized* (i.e., sent to the Curtis factory for characterization on the motor dyno), Field Weakening Drive can be set anywhere in the range of 0% (lowest torque, highest efficiency) to 100% (highest torque, lowest efficiency). *If the ACIM motor was auto characterized* (i.e., characterized using the ACIM motor characterization procedure in Chapter 8A), the range is restricted by the results of the Field Weakening Test. For these motors, Field Weakening Drive can be set anywhere in the range of 0% (lowest torque, highest efficiency) to Max Field Weakening Drive (highest torque, lowest efficiency) result. For auto characterized motors, setting Field Weakening Drive greater than the maximum setting found in the Field Weakening Test will result in poorer efficiency and less torque as the motor will be operating “over the slip curve.” NOTE: The Field Weakening Drive setting will have no effect at motor speeds below FW Base Speed.

MOTOR: 0 – ACIM: FIELD WEAKENING CONTROL MENU, cont'd

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Weakening Rate Drive *Field_Weakening_Rate_Drive* `0x383C 0x00`	0 – 100% *0 – 500*	Sets the control loop gains for field weakening. Setting the rate too low may create surging in the vehicle as it accelerates at mid to high speeds. Setting the rate too high may create high frequency oscillations (usually audible) when the vehicle accelerates at mid to high speeds.
Min Field Current *Min_Field_Current* `0x3821 0x00`	0 – 800 A *0 – 8000*	Sets the field current when no torque is requested from the motor. This current pre-fluxes the motor and can improve initial take-off at the expense of some battery consumption.

MOTOR: 0 – ACIM: SWAP TWO PHASES AND MOTOR TYPE PARAMETERS

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Swap Two Phases **PCF** *Swap_Two_Phases_OptionBits3* **[Bit 3]** `0x306C 0x00` **⚠ WARNING**	On / Off *On / Off*	If, after Swap Encoder Direction has been set correctly, the vehicle drives in the wrong direction (i.e., drives forward when in reverse, and vice versa), try changing the setting of the Swap Two Phases parameter. This parameter has the same effect as physically swapping the cables on any two of the three motor phase connections. **Positive motor speed must be in the forward direction in order for the emergency reverse feature to operate properly.** NOTE: Do not change this parameter while the controller is powering the motor. Any time this parameter is changed a Parameter Change Fault (fault code 49) is set and must be cleared by cycling power; this protects the controller and the operator. ***Adjusting this parameter can be hazardous. For instructions, see Chapter 7, Step 12 (page 84).***
Motor Type **PCF** *IM_Motor_Type* `0x3809 0x00`	0 – 324 *0 – 324*	This parameter references a predefined table of motor parameters for many AC induction motors. Presently, 323 motors are defined for os31. Motor Type 0 is reserved for using the auto-characterization procedure in Chapter 8A. **NOTE: Changing this parameter requires the re-setting of the FW Base Speed parameter (page 56). Other parameters may also need to be reset or evaluated by following the Initial Setup and Tuning Guide chapters instructions.** Consult your Curtis distributor or support engineer for information how to set this parameter based on your application and motor.

MOTOR: 0 – ACIM: LOS (Limited Operating Strategy) MENU

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
LOS Upon Encoder Fault |*LOS_Upon_Encoder_Fault* |*LOS_Upon_Encoder_Fault_Bit0* **[Bit 0]** `0x308F 0x00`	On / Off *On / Off*	Limited Operating Strategy (LOS) is typically used to drive the vehicle back to a repair center at very low speeds in the event the motor encoder fails. Following an encoder failure ((either Encoder Fault (fault code 36) or Stall Detected (fault code 73)), and after the Interlock is cycled, the vehicle enters LOS mode thus allowing drive without motor encoder feedback. In LOS mode, the ability to achieve maximum torque—even for a very short time—is considered more important than smoothness. When LOS mode is entered, the Encoder LOS fault (fault code 93) becomes active and the encoder fault ((either Encoder Fault (fault code 36) or Stall Detected (fault code 73)) is cleared. When this parameter is programmed On, LOS mode will be entered in the event of an encoder fault followed by an Interlock cycle. When programmed Off, in the event of an encoder fault the encoder fault remains and drive is disabled.
LOS Max Speed *Enc_LOS_Max_Speed* `0x3083 0x00`	100 – 2000 rpm *100 – 2000*	This parameter indirectly defines the maximum speed for LOS mode by setting the maximum frequency that corresponds to LOS Max Speed. In LOS mode the throttle commands a frequency that is interpolated linearly between zero (at Throttle Command = 0%) and the programmed LOS Max Speed (at Throttle Command = 100%).
LOS Max Current *Enc_LOS_Max_Current* `0x3085 0x00`	100 – 650 A *1000 – 6500*	In LOS mode, a partial or full throttle command will result in the maximum current set by this parameter. This current setting is clamped by the controller's rated current.
LOS Max Mod Depth *Enc_LOS_Max_Mod_Depth* `0x3084 0x00`	15 – 100% *177 – 1182*	In LOS mode, the maximum modulation depth acts to limit the current at higher speeds. This parameter should be set such that the modulation depth limit is reached prior to the LOS Max Speed limit, so that the motor current will fall off from LOS Max Current at higher speeds. This may allow the vehicle to drive longer in LOS mode, as it lessens the chance of the motor or controller overheating.
LOS Accel Rate **Enc_LOS_Accel_Rate** `0x3086 0x00`	2.0 – 15.0 s *2000 – 15000*	Defines the rate (in seconds) at which the frequency increases when full throttle is applied, while operating in LOS mode. This parameter should be set to a slow rate (high parameter value) so the frequency command has a very slow slew rate to ensure that the max torque point is hit for a reasonable period of time; this decreases the probability of going over the slip curve, and allows ramps or obstacles to be overcome.
LOS Decel Rate *Enc_LOS_Decel_Rate* `0x3087 0x00`	2.0 – 15.0 s *2000 – 15000*	Defines the rate (in seconds) at which the frequency decreases when throttle is released, while operating in LOS mode.

MOTOR: 1 – SPM (SURFACE PM MOTOR) CHARACTERIZATION TESTS MENU

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Test Enable *PMAC_AutoChar_Test_Enable** `0x3862 0x00`	0 – 1 *0 – 1*	This parameter is used to start the SPM motor characterization procedure. See Chapter 8B for the complete description of the SPM motor characterization procedure.
Test Throtte *PMAC_Test_Throttle** `0x30D1 0x00`	–1 – 1 *–1 – 1*	Begins characterization if a Test Enable is asserted. This parameter is used to change the direction of the motor to the forward direction during SPM motor characterization. **Important:** If the motor starts to turn in the **positive-rpm** vehicle speed direction, set Test Throttle = **1**. If it turns in the **negative-rpm** direction, set Test Throttle = **–1**. See Chapter 8B for the complete description of the ACIM motor characterization procedure and how this parameter is used.
Max Test Speed *PMAC_AutoChar_Max_Test_Speed** `0x38C1 0x00`	1000 – 6000 rpm *1000 – 6000*	This parameter is used to set the maximum motor speed allowed during SPM motor characterization. See Chapter 8B for the complete description of the SPM motor characterization procedure and how this parameter is used.
Max Test Current *PMAC_AutoChar_Max_Test_Current** `0x38C2 0x00`	10 – 30% *3277 – 9831*	This parameter is used to set the maximum motor speed allowed during SPM motor characterization. See Chapter 8B for the complete description of the SPM motor characterization procedure and how this parameter is used.

** Note: revised variable name for os31 (i.e., the "PMAC" part of the variable name was "SPM" in os30, and was added for "Test_Throttle"). The terms Surface Permanent Magnet (SPM) and Permanent Magnet AC (PMAC) motors used within this manual refer to the same motor technology.*

Quick Links:
Chapter 8B p.91
SPM Motor
Characterization

MOTOR FEEDBACK OPTIONS

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Feedback Type *Feedback_Type* `0x382E 0x00`	1 – 2 *1 – 2*	Set this parameter to the type of position feedback device in your vehicle: 1 = quadrature encoder 2 = Sin/Cos sensor. NOTE: A Parameter Mismatch Fault will result unless the Feedback Type matches the Motor Technology setting (see page 55): If Motor Technology = 0 (ACIM), then Feedback Type must = 1 (quadrature encoder). If Motor Technology = 1 (SPM), then Feedback Type must = 2 (Sin/Cos sensor).
Swap Feedback Direction **PCF** *Swap_Feedback_Direction* *OptionBits3* **[Bit 0]** `0x306C 0x00` ⚠ **WARNING**	On / Off *On / Off*	Changes the motor encoder's effective direction of rotation. The encoder provides data used to calculate motor position and speed. This parameter must be set such that when the motor is turning forward, the controller reports back a positive motor speed. **Positive motor speed must be in the forward direction in order for the emergency reverse feature to operate properly.** NOTE: Do not change this parameter while the controller is powering the motor. Any time this parameter is changed a Parameter Change Fault (fault code 49) is set and must be cleared by cycling power; this protects the controller and the operator. ***Adjusting this parameter can be hazardous. For instructions, see Chapter 7, Step 10 (page 83).***

MOTOR FEEDBACK 1 – ENCODER MENU

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Encoder Steps **PCF** *Encoder_Steps* `0x304B 0x00` ⚠ **WARNING**	32 – 256 *32 – 256*	Sets the number of encoder pulses per revolution. This must be set to match the encoder; see motor nameplate or its technical data for this information. NOTE: Do not change this parameter while the controller is powering the motor. Any time this parameter is changed a Parameter Change Fault (fault code 49) is set and must be cleared by cycling power; this protects the controller and the operator. ***Adjusting this parameter can be hazardous; setting it improperly may cause vehicle malfunction, including uncommanded drive. For instructions, see Chapter 7, Step 8 (page 82–83).***

MOTOR FEEDBACK 1 – ENCODER: ENCODER FAULT SETUP MENU

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Fault Detection Enable *Encoder_Fault_Detection_Enable* *Encoder_Fault_Detection_Enable_Bit0* **[Bit 0]** 0x389C 0x00	On / Off *On / Off*	When programmed On, encoder fault checking is enabled. Three fault conditions are checked: Encoder Fault (fault code 36, Stall Detected (fault code 73), and Encoder Pulse Error (fault code 88).
Encoder Pulse Fault Detect Time *Encoder_Pulse_Fault_Detect_Time* 0x393E 0x00	0.0 – 3.0 s *0 – 94*	Defines the minimum time it takes for the controller, while the vehicle is in motion, to detect that the encoder and the Encoder Steps parameter do not match. When the Encoder Steps setup is incorrect, the motor controller cannot properly calculate AC motor field orientation. The loss of field orientation can cause the motor to spin up toward full speed once any throttle is applied. This parameter sets a timer that starts once the throttle has been moved and then released, the drive current is significant, and the motor is still accelerating. Note that the motor can spin at high rpm for several seconds before conditions allow the controller to properly detect a fault. An Encoder Pulse Error (fault code 88) is declared when this fault is detected. Setting the parameter to zero will disable this fault detection.
Fault Stall Time *Enc_Fault_Stall_Time* 0x3089 0x00	0 – 10 s *0 – 5000*	Sets a timer when no motor encoder movement is detected. In Speed Modes: If no motor encoder movement is detected for the programmed Fault Stall Time, a Stall Detected fault (fault code 73) is issued. In Torque Mode: If no motor encoder movement is detected for the programmed Fault Stall Time, with maximum throttle applied, a Stall Detected fault (fault code 73) is issued.

MOTOR FEEDBACK 2 – SIN/COS MENU

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Sin Cos Fault Threshold *Sin_Cos_Fault_Threshold* 0x3878 0x00	5.0 – 20.0% *51 – 205*	Defines the allowable percent change in the Sin or Cos feedback. A Sin/Cos Sensor Fault (fault code 36) is declared if this threshold exceeded five times sequentially. The default value is 12.0%.
Sin Cos Fault Threshold High *Sin_Cos_Fault_Threshold_High* 0x38CD 0x00	20.0 – 100.0% *205 – 1024*	Defines the % allowable change in the SIN or COS feedback (high value used for first 30 seconds after interlock). This will allow the controller to adjust for slight variances if the sensor was changed. **This is a new parameter for os31.**
Sin Cos Fault Time *Sin_Cos_Fault_Time* 0x38CE 0x00	10 – 1000 ms *10 – 1000*	A Sin Cos Sensor fault (fault 36) will be generated if the sensor is outside the tolerance for 10ms during this amount of time. **This is a new parameter for os31.**
Sin Min* *Feedback_Sin_Min* 0x3863 0x00	0 – 100% *0 – 1023*	Minimum output by the Sin/Cos sensor on the Sin channel. Input detected at Position Feedback A (pin 31). The value is set during the SPM motor characterization procedure. The default value is zero.
Sin Max* *Feedback_Sin_Max* 0x385C 0x00	0 – 100% *0 – 1023*	Maximum output by the Sin/Cos sensor on the Sin channel. Input detected at Position Feedback A (pin 31). The value is set during the SPM motor characterization procedure. The default value is zero.
Cos Min* *Feedback_Cos_Min* 0x385F 0x00	0 – 100% *0 – 1023*	Minimum output by the Sin/Cos sensor on the Cos channel. Input detected at Position Feedback B (pin 32). The value is set during the SPM motor characterization procedure. The default value is zero.
Cos Max* *Feedback_Cos_Max* 0x382F 0x00	0 – 100% *0 – 1023*	Maximum output by the Sin/Cos sensor on the Cos channel. Input detected at Position Feedback B (pin 32). The value is set during the SPM motor characterization procedure. The default value is zero.

** These are read-only parameters, useful when cloning controllers to verify these settings, and if the proper SPM (PMAC) auto-characterization was preformed.*

The four Sin/Cos Min and Max parameters' default value is zero. This prevents the running of SPM/PMAC motors without performing the auto-characterization.

See Chapter 8B for the SPM/PMAC Auto Characterization procedure.

Contact your Curtis distributor or support engineer to resolve any Sin/Cos sensor errors or their parameter values.

MOTOR: TEMPERATURE CONTROL MENU

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Sensor Enable *MotorTemp_Sensor_Enable* *OptionBits3* **[Bit 1]** `0x306C 0x00`	On / Off *On / Off*	When programmed On, the motor temperature cutback and the motor temperature compensation features are enabled. This parameter can be used only if a temperature sensor has been properly configured. The motor temperature cutback feature will linearly cut back the current from 100% to 0% between the Temperature Hot and Temperature Max temperatures. The motor temperature compensation feature will adapt the motor control algorithms to varying motor temperatures, for improved efficiency and more consistant performance.
Sensor Type *MotorTemp_Sensor_Type* `0x307B 0x00` **NOTICE**	1 – 5 *1 – 5*	Five sensor types are predefined in the software:. Type 1 KTY83–122 Type 2 2× Type 1, in series Type 3 KTY84–130 or KTY84–150 Type 4 2× Type 3, in series Type 5 PT1000. Custom sensor types can be set up easily, if none of the five predefined types is appropriate for your application. Please contact your Curtis distributor or support engineer. NOTE: The industry standard KTY temperature sensors are silicon temperature sensors with a polarity band; **the polarity band of a KTY sensor must be the end connected to I/O Ground** (pin 7).
Sensor Offset *MotorTemp_Sensor_Offset* `0x305A 0x00`	–20 – 20°C *–200 – 200*	Often the sensor is placed in the motor at a location with a known offset to the critical temperature; the offset can be corrected with this parameter. The parameter can also be used to correct a known offset in the sensor itself.
Braking Thermal Cutback Enable *MotorBrakingThermalCutback_Enable* *MotorBrakingThermalCutback_Enable_Bit0* **[Bit0]** `0x386C 0x00`	On / Off *On / Off*	When programmed On, drive current and regen braking current will be cut back based on motor temperature. All forms of regen braking current (Regen_Current_Limit, Brake_Current_Limit, EMR_Current_Limit, Interlock_Brake_Current_Limit) includes emergency reverse braking, interlock braking, brake input braking, direction reversal braking, neutral braking, and speed limit braking. When programmed Off, only drive current (and not regen braking current) will be cut back based on motor temperature. If the vehicle has mechanical brakes, setting this parameter to On may help reduce motor heating.
Temperature Hot *MotorTemp_Hot* `0x304E 0x00`	0 – 250°C *0 – 2500*	Defines the temperature at which current cutback begins.
Temperature Max *MotorTemp_Max* `0x304F 0x00`	0 – 250°C *0 – 2500*	Defines the temperature at which current is cut back to zero.
MotorTemp LOS Max Speed *MotorTemp_LOS_Max_Speed* `0x308A 0x00`	100 – 3000 rpm *100 – 3000*	When a Motor Temp Sensor Fault (fault code 29) is set, a LOS (Limited Operating Strategy) mode is engaged. The maximum speed is reduced to the programmed Max Speed in the operating mode (Max_Speed_SpdMx, Max_Speed_SpdM, Max_Speed_TrqM) or to \the MotorTemp_LOS_Max_Speed, whichever is lower.

BATTERY MENU

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Nominal Voltage *Nominal_Voltage* `0x3048 0x00`	24 – 96 V *1536 – 6144*	Must be set to the vehicle’s nominal battery pack voltage. This parameter is used in determining the overvoltage and undervoltage protection thresholds for the electronic system. See page 25 for Over, Under, and Brownout voltage definitions and constraints. NOTE: In all cases the OS default Nominal Voltage is the highest value in the controller’s range (See Table D-1). Always check and adjust this parameter whenever using a lower nominal voltage. Scaling is 64 counts per volt. For example, controller 1238E-65XX has a 48–80 voltage range. Therefore, when using a 48 volt battery, the *Nominal_Voltage* parameter will be 3072 (64 × 48 = 3072) in your VCL program, or as the raw (decimal) value in TACT.
Kp UV *Batt_Kp_UV* `0x380E 0x00`	0.0 – 100.0% / V *0 – 1024*	When the battery voltage goes below the undervoltage threshold (page 25), a closed loop PI (Proportional/Integral) controller is enabled in an attempt to keep the battery voltage from drooping. It accomplishes this by cutting back the drive current, thereby reducing the load on the battery. The Kp term is the proportional gain and is set in units of % cutback per volt; for example, a setting of 25 would provide full current cutback with 4 V of droop. The Ki term is the integral gain. Integral gain will accumulate the voltage droop and attempt to bring the battery droop back to 0 V. Higher gains will react more strongly and quickly. Typically, Kp UV and Ki UV are used together to provide the best response. If the linear response of the previous AC controllers is preferred, set Ki UV = 0.
Ki UV *Batt_Ki_UV* `0x380F 0x00`	0 – 100% *0 – 16384*	
User Overvoltage *User_Overvoltage* `0x3049 0x00`	105 – 200% *269 – 512*	The value of this parameter is a percentage of the Nominal Voltage setting. The User Overvoltage parameter can be used to adjust the overvoltage threshold, which is the voltage at which the controller will cut back regen braking to prevent damage to the electrical system. Typically this parameter is changed only when the controller is being used in an application at the low end of the controller’s range: such as a 48–80V controller being used in a system with a 48 V battery pack. In this case, the overvoltage threshold can be raised by setting the User Overvoltage to a higher value. The overvoltage threshold can never be raised above the controller’s power base maximum voltage rating.
User Undervoltage *User_Undervoltage* `0x304A 0x00`	0 – 95% *0 – 242*	The value of this parameter is a percentage of the Nominal Voltage setting. The User Undervoltage parameter can be used to adjust the undervoltage threshold, which is the voltage at which the controller will cut back drive current to prevent damage to the electrical system. Typically this parameter is changed only when the controller is being used in an application at the high end of the controller’s range: such as a 24–36 V controller being used in a system with a 36V battery pack. In this case, the undervoltage threshold can be lowered by setting the User Undervoltage to a lower value. The undervoltage threshold can never be lowered below the controller’s power base minimum voltage rating.

BATTERY MENU, cont'd

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Reset Volts Per Cell *BDI_Reset_Volts_Per_Cell* `0x3170 0x00`	0.900 – 3.000 V *900 – 3000*	The reset voltage level is checked only once, when the main contactor first closes. Note that the BDI Reset Percent parameter also influences the algorithm that determines whether BDI Percentage is reset to 100%. Reset Volts Per Cell should always be set higher than Full Volts Per Cell. Reset Voltage Level = Reset Volts Per Cell × number of cells in the battery pack.*
Full Volts Per Cell *BDI_Full_Volts_Per_Cell* `0x3171 0x00`	0.900 – 3.000 V *900 – 3000*	The full voltage level sets the B+ (capacitor voltage) that is considered to be 100% state-of-charge; when a loaded battery drops below this voltage, it begins to lose charge. Capacitor Voltage is viewable in the programmer's Monitor » Battery menu. Full Voltage Level = Full Volts Per Cell × number of cells in the battery pack.*
Empty Volts Per Cell *BDI_Empty_Volts_Per_Cell* `0x3172 0x00`	0.900 – 3.000 V *900 – 3000*	The empty voltage level sets the Capacitor Voltage that is considered to be 0% state-of-charge. Empty Voltage Level = Empty Volts Per Cell × number of cells in the battery pack.*
Discharge Time *BDI_Discharge_Time* `0x3173 0x00`	0 – 600 minutes *0 – 600*	Sets the minimum time for the BDI algorithm to count down the BDI Percentage from 100% to 0%. The BDI algorithm integrates the time the filtered capacitor voltage is below the state of charge voltage level. When that cumulative time exceeds the Discharge Time / 100, the BDI Percentage is decremented by one percentage point and a new state of charge voltage level is calculated. State of Charge Level = [(Full Voltage Level - Empty Voltage Level) x BDI Percentage / 100] + Empty Voltage Level.
BDI Reset Percent *BDI_Reset_Percent* `0x3174 0x00`	0 – 100% *0 – 100*	When a battery has a high BDI percentage, its float voltage at KSI On can sometimes cause false resets. The BDI Reset Percent parameter addresses this problem by allowing the user to define a BDI Percentage value above which the BDI Percentage variable will not reset. When KSI is first powered on, the BDI Percentage variable will reset to 100% only if ((Keyswitch Voltage > Reset Voltage Level) and (BDI Percentage < BDI Reset Percent)).

** To determine the number of cells in the battery pack, divide the Nominal Voltage setting (page 62) by the battery chemistry's nominal volts-per-cell. Lead-acid: 2.0 V/cell, nominal.*

Note: For non lead-acid batteries, including Lithium-Ion battery packs, use the pack's or cell manufacturer's approved Battery Management System (BMS) for determining BDI.

VEHICLE MENU

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Metric Units *Metric_Units* *OptionBits3* **[Bit 5]** `0x306C 0x00`	On / Off *On / Off*	When this parameter is programmed On, the distance variables (Vehicle Odometer, Braking Distance Captured, Distance Since Stop, Distance Fine, and the Capture Distance variables) will accumulate and display in metric units (km, meters, or decimeters). When programmed Off, the distance variables will accumulate and display in English units (miles, feet, or inches). Distance variables are displayed in the Monitor » Vehicle menu.
Speed to RPM *Speed_to_RPM* `0x304C 0x00`	10.0 – 3000.0 *100 – 30000*	This parameter affects the vehicle speed displayed in the Monitor » Motor menu, and also modifies the VCL variable Vehicle_Speed; it does not affect actual vehicle performance. The value entered for Speed to RPM is a conversion factor that scales motor speed to vehicle speed. KPH to RPM: (G/d)*5305, where G = gear ratio, d = tire diameter [mm]. MPH to RPM: (G/d)*336.1, where G = gear ratio, d = tire diameter [in].
Capture Speed 1 *Capture_Speed_1* `0x3079 0x00`	0 – 8000 rpm *0 – 8000*	The controller captures the time it takes the motor to go from 0 rpm to the programmed Capture Speed. The result is stored as “Time to Speed 1” in the Monitor » Vehicle menu. This timer starts every time the motor accelerates from zero speed.
Capture Speed 2 *Capture_Speed_2* `0x3886 0x00`	0 – 8000 rpm *0 – 8000*	This parameter allows a second capture speed to be defined, and works identically to Capture Speed 1. The result is stored as “Time to Speed 2” in the Monitor » Vehicle menu.
Capture Distance 1 *Capture_Distance_1* `0x307A 0x00`	1 – 1320 *1 – 1320*	The controller captures the time it takes the vehicle to travel from 0 rpm to the programmed Capture Distance. The result is stored as “Time to Dist 1” in the Monitor » Vehicle menu. This timer starts every time the vehicle accelerates from zero speed. Note: For accurate distance measuring, the Speed to RPM parameter must be set correctly. With the Metric Units parameter programmed Off, distance is in units of feet. With Metric Units programmed On, distance is in units of meters.
Capture Distance 2 *Capture_Distance_2* `0x3883 0x00`	1 – 1320 *1 – 1320*	This parameter allows a second capture distance to be defined, and works identically to Capture Distance 1. The result is stored as “Time to Dist 2” in the Monitor » Vehicle menu.
Capture Distance 3 *Capture_Distance_3* `0x3884 0x00`	1 – 1320 *1 – 1320*	This parameter allows a third capture distance to be defined, and works identically to Capture Distance 1. The result is stored as “Time to Dist 3”in the Monitor » Vehicle menu.

Quick Links:
Monitor » Vehicle Menu p.77
 Vehicle Speed
 Vehicle Odometer
 Time to Speed 1
 Time to Speed 2
 Time to Distance 1
 Time to Distance 2
 Time to Distance 3

EMERGENCY REVERSE MENU [SPEED MODE & SPEED MODE EXPRESS only]

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
EMR Enable |*EMR_Enable* |*OptionBits1* **[Bit 1]** `0x306A 0x00`	On / Off *On / Off*	Determines whether the emergency reverse function is active. On = emergency reverse is enabled. Off = emergency reverse is disabled.
EMR Type *EMR_Type* `0x3036 0x00`	0 – 3 *0 – 3*	Determines where the input comes from for emergency reverse. 0 = emergency reverse activated by switch 1 (pin 24). 1 = emergency reverse is activated by VCL functions \Enable_Emer_Rev() and Disable_Emer_Rev(). 2 = emergency reverse activated by switch 1 (pin 24), but only if the vehicle is moving forward (forks trailing) when emergency reverse is activated. 3 = emergency reverse is activated by VCL functions Enable_Emer_Rev() and Disable_Emer_Rev(), but only if the vehicle is moving forward (forks trailing) when emergency reverse is activated.
EMR Dir Interlock |*EMR_Dir_Interlock* |*EMR_Dir_Interlock_Bit0* **[Bit 0]** `0x389F 0x00`	On / Off *On / Off*	Determines whether the interlock switch must be turned off after emergency reverse before the vehicle can be driven again. On = interlock and throttle and direction must all be cleared. Off = only throttle and direction must be cleared.
EMR Time Limit *EMR_Time_Limit* `0x303B 0x00`	0.0 – 30.0 s *0 – 3750*	Defines how long emergency reverse is allowed to be active after the vehicle is moving in the reverse direction. This timer will restart if the vehicle ever goes forward while emergency reverse is still active. The allowable range is 0–30 seconds, where 30 seconds is a special case of no time out. When emergency reverse times out, the Emer Rev Timeout fault is set. Cycling the emergency reverse input will clear the Emer Rev Timeout fault. To stop the vehicle after an EMR event (not move in reverse direction), set this parameter to 0.
EMR Speed *EMR_Speed* `0x3038 0x00`	50 – 6000 rpm *50 – 6000*	Defines the maximum reverse speed of the motor (in motor rpm), when emergency reverse is active. The motor speed in reverse during an emergency reverse event will be the lesser of EMR_Speed and either Max_Speed_SpdMx (for Speed Mode Express) or Max_Speed_SpdM (for Speed Mode). Emergency Reverse is not valid for Torque Mode. See Fig.16, Control Mode Processing, on page 108.
EMR Accel Rate *EMR_Accel_Rate* `0x3039 0x00`	0.1 – 3.0 s *100 – 3000*	Sets the rate (in seconds) at which the vehicle accelerates in the opposite direction after it has been brought to a stop. If the vehicle is already traveling in the reverse direction below the EMR Speed, the EMR Accel Rate will bring the vehicle to the EMR Speed.
EMR Decel Rate *EMR_Decel_Rate* `0x303A 0x00`	0.1 – 3.0 s *100 – 3000*	Sets the rate (in seconds) at which the vehicle brakes to a stop when emergency reverse is activated and the vehicle is moving forward. If the vehicle is already traveling in the reverse direction above the EMR Speed, the EMR Decel Rate will bring the vehicle down to the EMR Speed.

INTERLOCK BRAKING MENU

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Enable *Interlock_Brake_Enable* *OptionBits3* **[Bit 7]** `0x306C 0x00`	On / Off *On / Off*	Determines whether the interlock braking function is active. On = The controller will attempt to bring the vehicle to a stop using regen braking when the interlock signal is removed. Off = The controller will disable the bridge after Sequencing Delay expires and allow the vehicle to roll freely when the interlock signal is removed. This option is typically used only when there is a user controlled mechanical or hydraulic brake system.
Decel Rate HS *Interlock_Brake_Decel_ Rate_HS* `0x309F 0x00`	0.1 – 30.0 s *100 – 30000*	Sets the rate (in seconds) that is used to slow down the vehicle when the interlock is released at high vehicle speeds (speeds > HS setting). Larger values represent slower response.
Decel Rate LS *Interlock_Brake_Decel_ Rate_LS* `0x309E 0x00`	0.1 – 30.0 s *100 – 30000*	Sets the rate (in seconds) that is used to slow down the vehicle when the interlock is released at low vehicle speeds (speeds < LS setting). Larger values represent slower response.
Interlock Brake Timeout *Interlock_Brake_Timeout* `0x309C 0x00`	0.0 – 8.0 s *0 – 1000*	Controls the maximum allowable duration of an interlock braking event. The timer starts as soon as the interlock signal is removed. If the time expires before the vehicle has slowed below the Set_Speed_Threshold, the EM brake will engage automatically. This timeout allows parallel usage of regen braking and the EM brake to reduce stopping distance. If Interlock Brake Timeout expires and the motor is still moving, regen braking will continue to retard vehicle motion in conjunction with the EM brake. NOTE: This parameter is only applicable when EM_Brake_Type = 1 or 2 (page 49).

Quick Links:

Speed Mode — Fine Tuning Menu p.36
  HS (High Speed)
  LS (Low Speed)

CAN INTERFACE MENU

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
CANopen Interlock *CANopen_Interlock_Enable* *OptionBits3* **[Bit 2]** `0x306C 0x00`	On / Off *On / Off*	When programmed On, CAN NMT State must = 5 (operational state) in order for the interlock to be set; see Monitor » CAN Status menu, page 78.
CAN Node ID 1 *CAN_Node_ID_1* `0x3140 0x00`	1 – 127 *1 – 127*	The Node ID for the primary microprocessor is determined by the state of switches 5 and 6 at KSI turn on: Node_ID_1 is selected when Sw 6 = Off and Sw 5 = Off Node_ID_2 is selected when Sw 6 = Off and Sw 5 = On Node_ID_3 is selected when Sw 6 = On and Sw 5 = Off Node_ID_4 is selected when Sw 6 = On and Sw 5 = On. If the selected parameter has a Node ID of zero, the Node_ID_1 parameter is used. If the Node_ID_1 parameter is also zero, a default ID of 38 is used.
CAN Node ID 2 *CAN_Node_ID_2* `0x3141 0x00`	1 – 127 *1 – 127*	See description of Node ID 1.
CAN Node ID 3 *CAN_Node_ID_3* `0x3146 0x00`	1 – 127 *1 – 127*	See description of Node ID 1.
CAN Node ID 4 *CAN_Node_ID_4* `0x3147 0x00`	1 – 127 *1 – 127*	See description of Node ID 1.
Supervisor Node ID *Supervisor_Node_ID* `0x3872 0x00`	1 – 127 *1 – 127*	Sets the Node ID for the supervisor microprocessor. The Node ID is the first 7 bits of the 11-bit identifier (the COB ID).
Baud Rate *CAN_Baud_Rate* `0x3142 0x00`	– 3 – 4 *– 3 – 4*	Sets the CAN baud rate for the CANopen Slave system: – 3 = 20 kbit/s, – 2 = 50 kbit/s, – 1 = 100 kbit/s, 0 = 125 kbit/s, 1 = 250 kbit/s, 2 = 500 kbit/s, 3 = 800 kbit/s, 4 = 1000 kbit/s.
Heartbeat Rate *CANopen_Heart_Beat_Rate* `0x1017 0x00`	16 – 200 ms *4 – 50*	Sets the rate at which the CAN heartbeat messages are sent from the CANopen Slave system.
PDO Timeout Period *CAN_PDO_Timeout_Period* `0x3149 0x00`	0 – 200 ms *0 – 50*	Sets the PDO timeout period for the CANopen Slave system. After the slave controller has sent a PDO-TX (MISO), it will declare a PDO Timeout Fault if the master controller has not sent a reply PDO-RX (MOSI) message within the set time. Either PDO1 MOSI or PDO2 MOSI will reset the timer. Setting the PDO Timeout Period = 0 will disable this fault check.
Emergency Message Rate *CANopen_Emergency_Rate* `0x3148 0x00`	16 – 200 ms *4 – 50*	Sets the minimum rate between CAN emergency messages from the CANopen Slave system. This prevents quickly changing fault states from generating so many emergency messages that they flood the CANbus.
Suppress CANopen Init *Suppress_CANopen_Init* `0x3143 0x00`	0 – 1 *0 – 1*	When Suppress CANopen Init is set = 1, at KSI On the initialization of the CANopen system is suppressed. Typically this is done so that the VCL program can make changes to the CANopen system before enabling it (by setting the variable Suppress_CANopen_Init = 0 and running the Setup_CAN( ) function).

RESET CONTROLLER PARAMETER

PARAMETER	ALLOWABLE RANGE	DESCRIPTION
Reset Controller *ResetController* `0x3B05 0x00`	0 – 1 *0 – 1*	Setting this parameter = 1 will reset the controller. This reset is similar to resetting by cycling the keyswitch. Reset Controller has the advantage of resetting without causing the parameter block to be reloaded into the 1313/1314 programmer.

CLONING CONTROLLERS

(for copying parameter settings to multiple controllers)

Once a controller has been programmed to the desired settings, these settings can be transferred as a group to other controllers, thus creating a family of "clone" controllers with identical settings.

Cloning only works between controllers with the same model number and software version. For example, the 1313/1314 programmer can read all the information from a 1236E-5421 controller and write it to other 1236E-5421 controllers; however, it cannot write that same information to 1236E-5521 or 1236SE-5621 controllers.

To perform cloning, plug the programmer (1313 or 1314) into the controller that has the desired settings. While the steps using the 1313 versus the 1314 are slightly different in terms of screen images, the basic concept is the same: Save the parameters from the controller to clone, which is the act of saving a ".CPF" file (Curtis Program File) using the Save/Save As . . . operations. When saving the CPF file, chose a file name with meaning as this CPF file is used to write (clone) its data to subsequent controllers.

For example, using the 1314 PC Programming Station, with the controller to be updated connected, select "open" in the File menu, then navigate to the above mentioned (saved) CPF file, which will be loaded (indicated) below the menus bar. In the Communication menu, select the "Save file to connected system (F6)" icon, and follow the prompts to copy the settings into the controller being cloned (i.e., the "connected System" or controller). The 1313 is slightly different, working off the SD card where the CPF file was saved versus the PC's hard drive, and then using the "Restore" feature to download the settings into the controller being cloned.

For cloning Dual Drive controllers, the Master controller parameters will also be loaded into Slave controller, then the parameters for the Slave-vs-Master must be adjusted using the 1313/1314, as corresponds to the differences between the master and slave dual-drive controllers. See the separate Dual Drive manual, p/n 53097-DD, for the specific steps to preform for cloning/setup of the Master and Slave Dual-Drive controllers.

Note: Using either programmer (1313/1314), the prompts will offer "Advanced Cloning" . . . . Advanced Cloning is advisable ONLY under the direction of your Curtis distributor or support engineer, because it restores all parameters, including those at a higher (hidden level). Due to possible conflicts, select "No" in the 1313 prompt, or do not "check" the box in the 1314).

Please contact your Curtis distributor or support engineer if there are any question on cloning controllers.

5 — MONITOR MENU

Through its Monitor menu, the 1313 handheld and 1314 PC programmers provide access to real-time data during vehicle operation. This information is helpful during diagnostics and troubleshooting, and also while adjusting programmable parameters and the vehicle's initial setup.

Table 4 Monitor Menu: 1313/1314 Programmer

INPUTS MENU .... p. 70

- — Throttle Command
- — Throttle Multiplier
- — Mapped Throttle
- — Throttle Pot
- — Brake Command
- — Mapped Brake
- — Pot2 Raw
- — PD Throttle
- — Steer Pot
- — Steer Angle (deg)
- — Interlock
- — Emer Rev
- — Analog 1
- — Analog 2
- — Switch 1
- — Switch 2
- — Switch 3
- — Switch 4
- — Switch 5
- — Switch 6
- — Switch 7
- — Switch 8
- — Driver 1 Input
- — Driver 2 Input
- — Driver 3 Input
- — Driver 4 Input
- — PD Input
- — DigOut6 Input
- — DigOut7 Input
- — Switch 16

OUTPUTS MENU .... p. 72

- — Analog Out
- — Digital Out 6
- — Digital Out 7
- — Driver 1 PWM
- — Driver 2 PWM
- — Driver 3 PWM
- — Driver 4 PWM
- — PD PWM
- — PD Current
- — 5 Volts
- — 12 Volts
- — Ext Supply Current
- — Pot Low

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- — BDI
- — Capacitor Voltage
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- — Motor RPM
- — Max Speed Controller Limit
- — Temperature
- — MotorSpeed A
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- — Sin Input A
- — Cos Input B
- — Rotor Postion

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- — Current (RMS)
- — Modulation Depth
- — Frequency
- — Temperature
- — Main State
- — EMBrake State
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- — VCL Error Module
- — VCL Error
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- — **CUTBACKS .... p. 76**
  - — Motor Temp Cutback
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  - — Motor RPM
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- — Vehicle Speed
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- — Time Between Speeds
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- — CAN Node ID
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- — PDO1 MOSI Byte Map
- — PDO1 MISO Byte Map
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Monitor Menu: INPUTS

VARIABLE	DISPLAY RANGE	DESCRIPTION
Throttle Command *Throttle_Command* `0x3216 0x00`	–100.0 – 100.0% *–32767 – 32767*	Throttle request to slew rate block.
Throttle Multiplier *Throttle_Multiplier* `0x3213 0x00`	–200.0 – 200.0% *–256 – 256*	Multiplies or divides the throttle signal; useful in VCL throttle processing (see Throttle Processing on page 104 and Figure 15 on page 105).
Mapped Throttle *Mapped_Throttle* `0x3211 0x00`	–100.0 – 100.0% *–32767 – 32767*	Mapped throttle request. (see Throttle Processing on page 104 and Figure 15 on page 105).
Throttle Pot *Throttle_Pot_Raw* `0x3215 0x00`	0.00 – 5.50 V *0 – 36044*	Voltage at throttle pot wiper (pin 16).
Brake Command *Brake_Command* `0x321A 0x00`	0.0 – 100.0% *0 – 32767*	Brake request to slew rate block. (see Brake Processing on page 106 and Figure 15 on page 105)
Mapped Brake *Mapped_Brake* `0x3212 0x00`	0.0 – 100.0% *0 – 32767*	Mapped brake request. (see Brake Processing on page 106 and Figure 15 on page 105)
Pot2 Raw *Pot2_Raw* `0x3217 0x00`	0.00 – 5.50 V *0 – 36044*	Voltage at pot2 wiper (pin 17).
PD Throttle *PD_Throttle* `0x3210 0x00`	0.00 – 100.00 % *0 – 32766*	Proportional driver current request. (see Interfacing the Proportional Current Driver and Figure 17 on page 109)
Steer Pot *Steer_Pot_Raw* `0x38BB 0x00`	0.00 – 6.25 V *0 – 32767*	Voltage at steer pot wiper (pin 17) on Dual Drive traction slave. (reference the Dual Drive supplement manual: 53097_E&SEDD_os31)
Steer Angle *Steer_Angle* `0x38BA 0x00`	–90 – 90 *–90 – 90*	Steer angle degrees calculated in Dual Drive traction master.
Interlock |*Interlock_State* |*System_Flags1* **[Bit 0]** `0x322B 0x00`	On / Off *On / Off*	Interlock input on or off. The source of the interlock input is determined by the Interlock Type parameter. from Switch 3 (pin 9) if Interlock Type = 0 from VCL function if Interlock Type = 1 from KSI (pin 1) if Interlock Type = 2.
Emer Rev |*EMR_State* |*System_Flags1* **[Bit 1]** `0x322B 0x00`	On / Off *On / Off*	Emergency reverse input on or off. The source of the emergency reverse input is determined by the EMR Type parameter: from Switch 1 (pin 24) if EMR Type = 0, or 2. from VCL function if EMR Type = 1.
Analog 1 *Analog1_Input* `0x3204 0x00`	0.00 – 10.00 V *0 – 1023*	Voltage at analog 1 (pin 24).
Analog 2 *Analog2_Input* `0x3205 0x00`	0.00 – 10.00 V *0 – 1023*	Voltage at analog 2 (pin 8).
Switch 1 |*Sw_1* |*Switches* **[Bit 0]** `0x3226 0x00`	On / Off *On / Off*	Switch 1 on or off (pin 24).
Switch 2 |*Sw_2* |*Switches* **[Bit 1]** `0x3226 0x00`	On / Off *On / Off*	Switch 2 on or off (pin 8).

Monitor Menu: INPUTS, cont'd

VARIABLE	DISPLAY RANGE	DESCRIPTION
Switch 3 |*Sw_3* |*Switches* **[Bit 2]** `0x3226 0x00`	On / Off *On / Off*	Switch 3 on or off (pin 9).
Switch 4 |*Sw_4* |*Switches* **[Bit 3]** `0x3226 0x00`	On / Off *On / Off*	Switch 4 on or off (pin 10).
Switch 5 |*Sw_5* |*Switches* **[Bit 4]** `0x3226 0x00`	On / Off *On / Off*	Switch 5 on or off (pin 11).
Switch 6 |*Sw_6* |*Switches* **[Bit 5]** `0x3226 0x00`	On / Off *On / Off*	Switch 6 on or off (pin 12).
Switch 7 |*Sw_7* |*Switches* **[Bit 6]** `0x3226 0x00`	On / Off *On / Off*	Switch 7 on or off (pin 22).
Switch 8 |*Sw_8* |*Switches* **[Bit 7]** `0x3226 0x00`	On / Off *On / Off*	Switch 8 on or off (pin 33).
Driver 1 Input |*Sw_9* |*Switches* **[Bit 8]** `0x3226 0x00`	On / Off *On / Off*	Driver 1 input on or off (pin 6).
Driver 2 Input |*Sw_10* |*Switches* **[Bit 9]** `0x3226 0x00`	On / Off *On / Off*	Driver 2 input on or off (pin 5).
Driver 3 Input |*Sw_11* |*Switches* **[Bit 10]** `0x3226 0x00`	On / Off *On / Off*	Driver 3 input on or off (pin 4).
Driver 4 Input |*Sw_12* |*Switches* **[Bit 11]** `0x3226 0x00`	On / Off *On / Off*	Driver 4 input on or off (pin 3).
PD Input |*Sw_13* |*Switches* **[Bit 12]** `0x3226 0x00`	On / Off *On / Off*	Proportional driver on or off (pin 2).
DigOut6 Input |*Sw_14* |*Switches* **[Bit 13]** `0x3226 0x00`	On / Off *On / Off*	Digital Out 6 input on or off (pin 19).
DigOut7 Input |*Sw_15* |*Switches* **[Bit 14]** `0x3226 0x00`	On / Off *On / Off*	Digital Out 7 input on or off (pin 20).
Switch 16 |*Sw_16* |*Switches* **[Bit 15]** `0x3226 0x00`	On / Off *On / Off*	Switch 16 on or off (pin 14).

Monitor Menu: OUTPUTS

VARIABLE	DISPLAY RANGE	DESCRIPTION
Analog Out *Analog_Output* `0x321D 0x00`	0.00 – 10.00 V *0 – 32767*	Voltage at Analog output (pin 30). Note: 1232E and 1232SE controllers do not include this Analog output.
Digital Out 6 |*Dig6_Output* |*System_Flags1* **[Bit 3]** `0x322B 0x00`	On / Off *On / Off*	Digital Out 6 output on or off (pin 19).
Digital Out 7 |*Dig7_Output* |*System_Flags1* **[Bit 4]** `0x322B 0x00`	On / Off *On / Off*	Digital Out 7 output on or off (pin 20).
Driver 1 PWM *PWM1_Output* `0x321F 0x00`	0 – 100% *0 – 32767*	Driver 1 PWM output (pin 6).
Driver 2 PWM *PWM2_Output* `0x3220 0x00`	0 – 100% *0 – 32767*	Driver 2 PWM output (pin 5).
Driver 3 PWM *PWM3_Output* `0x3221 0x00`	0 – 100% *0 – 32767*	Driver 3 PWM output (pin 4).
Driver 4 PWM *PWM4_Output* `0x3222 0x00`	0 – 100% *0 – 32767*	Driver 4 PWM output (pin 3).
PD PWM *PD_Output* `0x321E 0x00`	0 – 100% *0 – 32767*	Proportional driver PWM output (pin 2).
PD Current *PD_Current* `0x321C 0x00`	0.00 – 2.00 A *0 – 607*	Current at proportional driver (pin 2).
5 Volts *Five_Volts_Output* `0x3202 0x00`	0.00 – 6.25 V *0 – 1023*	Voltage at +5V output (pin 26).
12 Volts *Twelve_Volts_Output* `0x3522 0x00`	0.00 – 12.00 V *0 – 768*	Voltage at +12V output (pin 25).
Ext Supply Current *Ext_Supply_Current* `0x3229 0x00`	0 – 200 mA *0 – 800*	Combined current of the external +12V and +5V voltage supplies (pins 25 and 26).
Pot Low *Pot_Low_Output* `0x3203 0x00`	0.00 – 6.25 V *0 – 1023*	Voltage at pot low (pin 18).

Monitor Menu: BATTERY

VARIABLE	DISPLAY RANGE	DESCRIPTION
BDI *BDI_Percentage* `0x3308 0x00`	0 – 100% *0 – 100*	Lead-acid battery discharge indicator (BDI). Effectively the battery's remaining state-of-charge. NOTE: For non lead-acid batteries, including Lithium-Ion battery packs, use the pack's or cell manufacturer's approved Battery Management System (BMS) for determining the BDI
Capacitor Voltage *Capacitor_Voltage* `0x324C 0x00`	0.0 – 200.0 V *0 – 12800*	Voltage of controller's internal capacitor bank at B+ terminal.
Keyswitch Voltage *Keyswitch_Voltage* `0x324D 0x00`	0.0 – 105.0 V *0 – 10500*	Voltage at KSI (pin 1).

Monitor Menu: MOTOR

VARIABLE	DISPLAY RANGE	DESCRIPTION
Motor RPM *Motor_RPM_Display*	–12000 – 12000 rpm *–12000 – 12000*	Motor speed in revolutions per minute. Filtered for display on the 1313/1314. No CAN Index is assigned to this monitor variable. Possible usage for a tachometer, due to the filtered (smoothing) nature of this VCL variable over the Motor_RPM variable (see Motor RPM in monitor Controller » Motor Tuning » Motor_RPM, page 76).
Max Speed Controller Limit *Max_Speed_Controller_Limit* `0x3559 0x00`	0 – 12000 rpm *0 – 12000*	Displays the maximum allowed speed, which clamps the upper limit of the Max Speed parameters. It is the least of the three motor-speed constraints described on page 24.
Temperature *Motor_Temperature* `0x320B 0x00`	–100 – 300°C *–1000 – 3000*	Temperature sensor readout.
MotorSpeed A *MotorspeedA* `0x35D1 0x00`	–12000 – 12000 rpm *–12000 – 12000*	Motor encoder phase A speed in revolutions per minute. This can be used to verify that phase A of the encoder is operating correctly. MotorSpeed A should equal MotorSpeed B in a properly operating motor encoder. MotorSpeed A does not indicate direction.
MotorSpeed B *MotorspeedB* `0x35D2 0x00`	–12000 – 12000 rpm *–12000 – 12000*	Motor encoder phase A speed in revolutions per minute. This can be used to verify that phase B of the encoder is operating correctly. MotorSpeed B should equal MotorSpeed A in a properly operating motor encoder. MotorSpeed B does not indicate direction.
Sin Input A *encoder_sin_input_compensated* `0x38C5 0x00`	0 – 1023 *0 – 1023*	Input at Position Feedback A (pin 31).
Cos Input B *encoder_cos_input_compensated* `0x38C6 0x00`	0 – 1023 *0 – 1023*	Input at Position Feedback B (pin 32).
Rotor Position *rotor_position_raw* `0x38C7 0x00`	–32768 – 32767 *–32768 – 32767*	The displayed value will never exceed 4095. 0 – 4095 maps to mechanical 0°– 360°.

Monitor Menu: CONTROLLER

VARIABLE	DISPLAY RANGE	DESCRIPTION
Current (RMS) *Current_RMS* `0x3209 0x00`	0.0 – 1000.0 A *0 – 10000*	RMS current of the controller, taking all three phases into account.
Modulation Depth *Modulation_Depth* `0x3208 0x00`	0.0 – 100.0% *0 – 1182*	Percentage of available voltage being used.
Frequency *Frequency* `0x3206 0x00`	–500 – 500 Hz *–3000 – 3000*	Controller electrical frequency.
Temperature *Controller_Temperature* `0x322A 0x00`	–100 – 300°C *–1000 – 3000*	Controller internal temperature.
Main State *Main_State* `0x3223 0x00`	0 – 10 *0 – 10*	Main contactor state: 0 = open 1 = precharge 2 = weld check 3 = closing delay 4 = missing check 5 = closed (when Main Enable = On) 6 = delay 7 = arc check 8 = open delay 9 = fault 10 = closed (when Main Enable = Off).
EMBrake State *EMBrakeState* `0x3892 0x00`	0 – 4 *0 – 4*	EM brake state: 0 = engaged 1 = releasing 2 = released 3 = engaging 4 = engaged and vehicle stopped.
Regen *Regen_State* *System_Flags1* **[Bit 2]** `0x322B 0x00`	On / Off *On / Off*	On when regen braking is taking place; Off when it is not.
Master Timer *Master_Timer* `0x3160 0x00`	0 – 429496729.5 s *0 – 4294967295*	The master timer is a timer of the total hours the controller is powered on (keyswitch hours). The master timer is controlled by the OS software and cannot be reset.
VCL Error Module *Last_VCL_Error_Module* `0x3473 0x00`	0 – 65535 *0 – 65535*	A VCL Runtime Error (fault code 68) will store additional information about the cause of a VCL runtime error in the VCL Error Module and VCL Error variables. The resulting non-zero values can be compared to the runtime VCL module ID and error code definitions listed in the controller's OS SysInfo file, which should help pinpoint the VCL error that caused the runtime error.
VCL Error *Last_VCL_Error* `0x3472 0x00`	0 – 65535 *0 – 65535*	

Monitor Menu: CONTROLLER, cont'd

VARIABLE	DISPLAY RANGE	DESCRIPTION
Motor Characterization Error *Motor_Characterization_Error* `0x3899 0x00`	0 – 23* *0 – 23*	A Motor Characterization Fault (fault code 87) will store additional information in the Motor Characterization Error variable:* 0 = sequencing error. Normally caused by turning off Motor Characterization Test Enable before running the test. 1 = encoder signal seen but step size not auto-detected; set up Encoder Steps manually 2 = motor temp sensor fault 3 = motor temp hot cutback fault 4 = controller overtemp cutback fault 5 = controller undertemp cutback fault 6 = undervoltage cutback fault 7 = severe overvoltage fault 8 = encoder signal not seen, or one or both channels missing 9 = motor parameters out of characterization range. 20 = Sin/Cos sensor not found 21 = phasing not detected 22 = Sin/Cos sensor characterization failure 23 = started characterization procedure while motor rotating.
Parameter Mismatch Error *Parameter_Mismatch_Error* `0x388F 0x00`	0 – 2 *0 – 2*	A Parameter Mismatch Fault Fault (fault code 99) will store additional information in the Parameter Mismatch Error variable: 0 = none 1 = Dual Motor Enable = On, and Control Mode Select is not set to either 0-Speed Mode Express or 1-Speed Mode 2 = Feedback Type is incompatible with Motor Technology setting.
Supervision Error *Supervision_Error* `0x3897 0x00`	0 – 4 *0 – 4*	A Supervision Fault (fault code 77) will store additional information in the Supervision Error variable: 0 = none 1 = watchdog timeout comms 2 = power supply fault detected 3 = queue fault detected 4 = ALU fault detected. The Supervisor Fault (flash code 77) has several causes. The most common cause is when one of the digital inputs is stuck in the range between the guaranteed high threshold and the guaranteed low threshold for more than 100 milliseconds. See Digital Input specifications, page 14.

*NOTES:
Errors 1 and 9 apply to ACIM motors only.
Errors 20–23 apply to SPM motors only.
Errors indicate the motor characterization data is invalid, except in the case of Error 1.
This monitor variable will read "0" during normal operation (i.e., no characterization fault code 87).

Monitor Menu: CUTBACKS

VARIABLE	DISPLAY RANGE	DESCRIPTION
Motor Temp Cutback *MotorTempCutback* `0x3581 0x00`	0 – 100% *0 – 4096*	Displays the current available as a result of \the motor temperature cutback function. A value of 100% indicates no cutback in current.
Controller Temp Cutback *ControllerTempCutback* `0x35F3 0x00`	0 – 100% *0 – 4096*	Displays the current available as a result of the controller temperature cutback function. A value of 100% indicates no cutback in current.
Undervoltage Cutback *UndervoltageCutback* `0x3605 0x00`	0 – 100% *0 – 4096*	Displays the current available as a result of the undervoltage cutback function. A value of 100% indicates no cutback in current.
Overvoltage Cutback *OvervoltageCutback* `0x3604 0x00`	0 – 100% *0 – 4096*	Displays the current available as a result of the overvoltage cutback function. A value of 100% indicates no cutback in current.

Monitor Menu: MOTOR TUNING

VARIABLE	DISPLAY RANGE	DESCRIPTION
Motor RPM *Motor_RPM* `0x3207 0x00`	–32768 – 32767 rpm *–32768 – 32767*	Motor speed in revolutions per minute. This is the raw value (compare to the filtered value under the Motor menu, page 73). Use Motor_RPM for VCL and CAN applications.
Base Speed Captured *Base_Speed_Captured* `0x35BE 0x00`	0 – 65535 rpm *0 – 65535*	Displays the value of the motor base speed captured in the most recent acceleration. This value is used to set the FW Base Speed parameter, using the FW Base Speed set procedure described on page 56 or using the ACIM motor characterization procedure (Chapter 8A).
Test Field Current *Test_Field_Current* `0x3873 0x00`	0 – 800 A *0 – 800*	Field test current reading to be used during the ACIM motor characterization procedure (Chapter 8A).

Monitor Menu: VEHICLE

VARIABLE	DISPLAY RANGE	DESCRIPTION
Vehicle Speed *Vehicle_Speed* `0x320A 0x00`	–3276.8 – 3276.7 *–32768 – 32767*	Vehicle speed, in units of MPH or KPH, depending on the setting of the Metric Units parameter (see Program » Vehicle menu). For accurate speed estimates, the Speed to RPM parameter must be set correctly.
Vehicle Odometer *Vehicle_Odometer* `0x3200 0x00`	0.0 – 10000000.0 *0 – 100000000*	Vehicle distance traveled, in units of miles or km, depending on the setting of the Metric Units parameter in the Vehicle parameters menu. For accurate distance measurements, the Speed to RPM parameter must be set correctly.
Vehicle Acceleration *Vehicle_Acceleration* `0x35C1 0x00`	0.000 – 10.000 g *0 – 10000*	Vehicle acceleration. This is a calculated value. The Speed to RPM parameter must be set correctly for an accurate measurement.
Time to Speed 1 *Time_to_Capture_Speed_1* `0x35BF 0x00`	0.00 – 128.00 s *0 – 32000*	Time taken for the vehicle to go from zero rpm to the programmed Capture Speed 1 (see Program » Vehicle menu) during its most recent such acceleration.
Time to Speed 2 *Time_to_Capture_Speed_2* `0x35BB 0x00`	0.00 – 128.00 s *0 – 32000*	Time taken for the vehicle to go from zero rpm to the programmed Capture Speed 2 (see Program » Vehicle menu) during its most recent such acceleration.
Time Between Speeds *Time_Between_Capture_ Speeds* `0x35C4 0x00`	0.00 – 128.00 s *0 – 32000*	Time taken for the vehicle to go from programmed Capture Speed 1 to programmed Capture Speed 2 (see Program » Vehicle menu) during its most recent such acceleration.
Time to Dist 1 *Time_to_Capture_Distance_1* `0x3612 0x00`	0.00 – 128.00 s *0 – 32000*	Time taken for the vehicle to travel from zero rpm to the programmed Capture Distance 1 (see Program » Vehicle menu) during its most recent such trip. For accurate distance measurements, the Speed to RPM parameter must be set correctly.
Time to Dist 2 *Time_to_Capture_Distance_2* `0x3613 0x00`	0.00 – 128.00 s *0 – 32000*	Time taken for the vehicle to travel from zero rpm to the programmed Capture Distance 2 (see Program » Vehicle menu) during its most recent such trip. For accurate distance measurements, the Speed to RPM parameter must be set correctly.
Time to Dist 3 *Time_to_Capture_Distance_3* `0x3614 0x00`	0.00 – 128.00 s *0 – 32000*	Time taken for the vehicle to travel from zero rpm to the programmed Capture Distance 3 (see Program » Vehicle menu) during its most recent such trip. For accurate distance measurements, the Speed to RPM parameter must be set correctly.
Braking Distance Captured *Braking_Distance_Captured* `0x3201 0x00`	0.0 – 1000000.0 *0 – 40000000*	Distance traveled by the vehicle starting with vehicle braking (initiated by throttle reversal, brake pot, VCL_Brake, or interlock braking) and ending when Motor_RPM = 0. Units are meters or feet, depending on the setting of the Metric Units parameter. For accurate distance measurements, the Speed to RPM parameter must be set correctly.
Distance Since Stop *Distance_Since_Stop* `0x324E 0x00`	0.0 – 1000000.0 *0 – 40000000*	Distance traveled by the vehicle starting from a stop. In effect, the vehicle is used as a tape measure. (In other words, if you travel 300 feet forward and then 300 feet in reverse, the distance would be 600.) The distance is continuously updated and will stop (and restart) when Motor_RPM = 0. For accurate distance measurements, the Speed to RPM parameter must be set correctly. Units are meters or feet, depending on the setting of the Metric Units parameter.
Distance Fine *Distance_Fine_Long* `0x3616 0x00`	–214748364.8 – 214748364.7 *–2147483648 – 2147483647*	Position measurement. Net distance in both the forward and reverse directions. (In other words, if you travel 20 inches forward and then 20 inches in reverse, the distance would be zero.) The distance is continuously updated and will roll over when the variable goes over the limits. Resets to zero on key cycle. Units are decimeters or inches, depending on the setting of the Metric Units parameter. For accurate distance measurements, the Speed to RPM parameter must be set correctly.

NOTE: All vehicle calculations assume no tire slippage.

Quick Links:

Vehicle Menu parameters p.64
Metric Units
Speed to RPM
Capture Speed 1, 2
Capture Distance 1, 2, 3

Monitor Menu: CAN STATUS

VARIABLE	DISPLAY RANGE	DESCRIPTION
CAN Node ID *CAN_Node_ID* `0x3145 0x00`	0 – 127 *0 – 127*	Displays the controller's Node ID.
CAN NMT State *CAN_NMT_State* `0x3328 0x00`	0 – 127 *0 – 127*	Controller CAN NMT state: 0=initialization, 4=stopped, 5=operational, 127=pre-operational.
PDO1 MOSI Byte Map*	0 – 2^{32}	Mapping objects for PDO1 MOSI's eight bytes.
PDO1 MISO Byte Map*	0 – 2^{32}	Mapping objects for PDO1 MISO's eight bytes.
PDO2 MOSI Byte Map*	0 – 2^{32}	Mapping objects for PDO2 MOSI's eight bytes.
PDO2 MISO Byte Map*	0 – 2^{32}	Mapping objects for PDO2 MISO's eight bytes.

** Each of these byte maps is a submenu containing 8 variables, one for each byte. Each variable is 32 bits.*

PDO1 MOSI Byte Map

CAN_PDO_MOSI_1_MAP_1	`0x1600 0x01`
CAN_PDO_MOSI_1_MAP_2	`0x1600 0x02`
CAN_PDO_MOSI_1_MAP_3	`0x1600 0x03`
CAN_PDO_MOSI_1_MAP_4	`0x1600 0x04`
CAN_PDO_MOSI_1_MAP_5	`0x1600 0x05`
CAN_PDO_MOSI_1_MAP_6	`0x1600 0x06`
CAN_PDO_MOSI_1_MAP_7	`0x1600 0x07`
CAN_PDO_MOSI_1_MAP_8	`0x1600 0x08`

PDO1 MISO Byte Map

CAN_PDO_MISO_1_MAP_1	`0x1A00 0x01`
CAN_PDO_MISO_1_MAP_2	`0x1A00 0x02`
CAN_PDO_MISO_1_MAP_3	`0x1A00 0x03`
CAN_PDO_MISO_1_MAP_4	`0x1A00 0x04`
CAN_PDO_MISO_1_MAP_5	`0x1A00 0x05`
CAN_PDO_MISO_1_MAP_6	`0x1A00 0x06`
CAN_PDO_MISO_1_MAP_7	`0x1A00 0x07`
CAN_PDO_MISO_1_MAP_8	`0x1A00 0x08`

PDO2 MOSI Byte Map

CAN_PDO_MOSI_2_MAP_1	`0x1601 0x01`
CAN_PDO_MOSI_2_MAP_2	`0x1601 0x02`
CAN_PDO_MOSI_2_MAP_3	`0x1601 0x03`
CAN_PDO_MOSI_2_MAP_4	`0x1601 0x04`
CAN_PDO_MOSI_2_MAP_5	`0x1601 0x05`
CAN_PDO_MOSI_2_MAP_6	`0x1601 0x06`
CAN_PDO_MOSI_2_MAP_7	`0x1601 0x07`
CAN_PDO_MOSI_2_MAP_8	`0x1601 0x08`

PDO1 MISO Byte Map

CAN_PDO_MISO_2_MAP_1	`0x1A01 0x01`
CAN_PDO_MISO_2_MAP_2	`0x1A01 0x02`
CAN_PDO_MISO_2_MAP_3	`0x1A01 0x03`
CAN_PDO_MISO_2_MAP_4	`0x1A01 0x04`
CAN_PDO_MISO_2_MAP_5	`0x1A01 0x05`
CAN_PDO_MISO_2_MAP_6	`0x1A01 0x06`
CAN_PDO_MISO_2_MAP_7	`0x1A01 0x07`
CAN_PDO_MISO_2_MAP_8	`0x1A01 0x08`

NOTE: MOSI (Master Out Slave In) = RX (Server to Client) in CANopen nomenclature
MISO (Master In Slave Out) = TX (Client to Server) in CANopen nomenclature
PDO mapping variables in os31, as listed above, use the MOSI and MISO nomenclature as shown.

6 — CONTROLLER INFORMATION MENU

This menu provides ID and version numbers for your controller hardware and software.

CONTROLLER INFORMATION MENU

VARIABLE	DISPLAY RANGE	DESCRIPTION
Serial Number *Serial_Number* `0x1018 0x04`	0 – 4294967295 *0 – 4294967295*	Serial number. For example, if the serial number printed on your controller is 15045L.11493, the Serial Number variable will have the value of 11493.
Model Number *Model Number* `0x3464 0x00`	0 – 4294967295 *0 – 4294967295*	Model number. For example, if you have a 1236E controller with the model number 1236E-4521, the Model Number variable will have a value of 12364521.
Mfg Date Code *Manuf_Date* `0x3466 0x00`	0 – 32767 *0 – 32767*	Controller date of manufacture, with the first two digits indicating the year and the last three indicating the day. For example, if the serial number printed on your controller is 15045L.11493, the Mfg Date Code variable will have the value of 15045 (45th day of 2015).
Hardware Version *Hardware_Ver* `0x3467 0x00`	0 – 32.767 *0 – 32767*	The hardware version number uniquely describes the combination of power base assembly and the logic, cap, and IMS board assemblies used in the controller.
OS Version *OS_Ver* `0x346A 0x00`	0 – 65535 *0 – 65535*	Version number of the operating system software that is loaded into the controller This variable specifies the major version number of the controller's operating system.
Build Number *TBuild_Number* `0x346B 0x00`	0 – 65535 *0 – 65535*	Build number of the operating system software that is loaded into the controller. This variable specifies the minor version number of the controller's operating system.
SM Version *SM_Ver* `0x332B 0x00`	0 – 327.67 *0 – 32767*	Version number of the Start Manager software that is loaded into the controller.
Param Blk Version *Param_Blk_Ver* `0x3468 0x00`	0 – 327.67 *0 – 32767*	Version number of the parameter block that is loaded into the controller.
VCL App Version *VCL_App_Ver* `0x3463 0x00`	0 – 327.67 *0 – 32767*	Version number of the VCL application software that is loaded into the controller. This value is set in the VCL program by assigning a value to the VCL_App_Ver variable.
Vehicle Serial Number *Vehicle_Serial_Number* `0x393D 0x00`	0 – 4294967295 *0 – 4294967295*	Provided for OEM use and definition.

7 — INITIAL SETUP

The 1232E/SE, 1234E/SE, 1236E/SE, and 1238E/SE controllers can be used in a variety of vehicles, which differ widely in characteristics. Before driving the vehicle, it is imperative that these initial setup procedures be carefully followed to ensure that the controller is set up to be compatible with your application.

BEFORE YOU START

Correct values for the motor parameters (Motor Type, FW Base Speed, and Field Weakening) must be determined individually for each motor.

***For ACIM motors*, use one of these three options to obtain ACIM motor data:**

- **Contact your Curtis distributor or support engineer with the manufacturer's part number for your motor. Curtis has a database of many motors for which the motor data has already been determined. Motors in the Curtis database are assigned a number, which is the number used for the ACIM Motor Type parameter.**
- **Send your ACIM motor to Curtis for testing on the factory motor dyno. Your motor's data will be entered into the Curtis database and we will send you software with the appropriate parameter values set to match your motor. Contact your Curtis distributor or support engineer before shipping your motor.**
- **Use the ACIM Motor Characterization Procedure (Chapter 8A), which has the controller "learn" the motor parameter data. The procedure should take about half an hour and can be done on the vehicle. Go ahead and complete setup steps 1 through 11 of the Initial Setup before conducting the ACIM characterization procedure.**

***For SPM motors*, use the SPM Motor Characterization Procedure (Chapter 8B), which has the controller "learn" the motor parameter data. The procedure should take about half an hour and can be done on the vehicle. Go ahead and complete steps 1 through 9 of the Initial Setup before conducting the SPM characterization procedure. Using the SPM Motor Characterization Procedure is the only option for obtaining motor data for SPM motors. Note, for SPM motors, there is no motor poles or feedback sensor direction parameters, as obtaining this data is part of the SPM auto-characterization routine.**

ACIM:

If Curtis has given you the values for Motor Type, FW Base Speed, and Field Weakening and you have set them on the controller (see ACIM Field Weakening Control menu, pages 56–57), complete the these initial setup procedures prior to fine-tuning the motor. If you will be using the automated Motor Characterization Procedure, that will come later—after you have completed steps 1 through 10. Following the motor characterization, complete the initial steps prior to completing the fine-tuning in Chapter 9.

SPM:

For SPM motor applications, start these initial setup procedures now. The SPM motor characterization will be preformed after you have completed steps 1 through 9. Then complete steps 12–14 prior to completing the fine-tuning in Chapter 9.

⚠ WARNING **Before beginning the setup procedures, jack the vehicle drive wheels up off the ground so that they spin freely and the vehicle is stable. Double-check all wiring to ensure it is consistent with the wiring guidelines presented in Chapter 2. Make sure all electrical and mechanical connections are tight.**

Turn on the controller and plug in the 1313 handheld or 1314 PC programmer.

Step 1: Motor Temperature Sensor (see page 61)

Set the Sensor Type parameter to the predefined type (1–5) that corresponds to your motor temperature sensor. Typically, the motor temperature sensor will be a thermistor that is connected from Analog 2 (pin 8) to I/O Ground (pin 7) as shown in figure 3.

Quick Links:
Monitor/Inputs Menu p.70
Monitor/Motor Menu p.73

To check whether the Sensor Type and Sensor Offset parameter settings and the motor-thermistor connections yield the correct motor temperature, ensure the motor's Sensor Enable parameter is set to On, then read the Temperature value displayed in the programmer's Monitor » Motor menu (page 73).

If the 1313/1314 programmer does not display the correct motor temperature, double-check the motor temperature control parameters Sensor Enable, Sensor Type, and Sensor Offset. Ensure that the thermistor's wiring orientation is as shown in Figure 3.

To setup a custom sensor type, VCL and an OS parameter-block change for a Sensor Type "Type 0" is required by your Curtis distributor or support engineer.

To proceed if the correct motor temperature is not displayed, if there is no motor temperature sensor, or while awaiting a custom sensor os/VCL, the initial setup procedure can continue only if the Sensor Enable parameter is set to Off.

If the 1313/1314 displays the correct motor temperature, complete this step by setting the remaining motor temperature control parameters: Sensor Offset (if not already completed, above), Braking Thermal Cutback Enable, Temperature Hot, Temperature Max, and MotorTemp LOS Max Speed.

Step 2: Current Limits (see page 43)

The Drive, Regen, Brake, EMR, and Interlock Current Limit parameters are a percentage of the controller's full rated current. The controller's full rated current is printed on the label of the controller. Set the five current limit parameters to your desired values.

Step 3: Battery (see page 62–63)

Set the Nominal Voltage parameter to match the nominal battery pack voltage of your system.

Step 4: Main Contactor (see pages 51–52)

Set up the parameters in the Drivers » Main Contactor Menu.

Step 5: EM Brake (see pages 49–50)

Set up the parameters in the EM Brake Control Menu.

Step 6: Throttle (see pages 20–23 and 46–47)

Quick Links:
Monitor/Inputs Menu p.70
Drivers/Main Contactor menu
  Main Interlock Type p.51
  Interlock Type p.52

Before the throttle can be setup, the interlock must be verified as Off. Read the Interlock value displayed in the Monitor » Inputs menu. If the 1313/1314 programmer indicates the interlock is On, review how you set the Interlock Type parameter (Drivers » Main Contactor Menu) and turn the interlock off. Verify that the programmer displays that the interlock is now Off.

Contact your Curtis distributor or support engineer to resolve any issues about the interlock before continuing with these initial setup procedures.

Quick Links:
Throttle parameters p.46–47
Throttle Type &
Wiring p.20–23
Monitor Inputs p.70
Throttle Pot
Mapped Throttle

Once the interlock has been verified Off, proceed to the throttle input setup. First set the Throttle Type parameter to match the type of throttle (1–5) and wiring used as described in Chapter 3, Throttle section. Then adjust the Forward Deadband, Forward Max, Reverse Deadband and Reverse Max parameters to match the range of the throttle. The Throttle Pot value displayed on the Monitor » Inputs menu is useful when setting up these parameters.

For the forward and reverse directions, read the displayed Throttle Pot voltage at the point when the throttle moves out of neutral and at the point just before full throttle and enter these values for the deadband and max settings for that direction. Set up the remaining parameters in the Throttle Menu as required by the application.

Verify that the throttle settings are correct by checking the Mapped Throttle value displayed in the Monitor » Inputs menu over the entire range of throttle pot movement. The value displayed for Mapped Throttle should be = 0% through the range of throttle motion that is considered neutral. The displayed Mapped Throttle should be = 100% through the range of motion that is considered maximum forward throttle and it is = –100% through the range considered maximum reverse throttle.

Contact your Curtis distributor or support engineer to resolve any issues about the throttle setup before continuing with the initial setup procedures.

Step 7: Brake (see page 48)

If the brake function is not used by your application, set the Brake Pedal Enable parameter = Off and Brake Type = 5.

Before the brake can be set up the interlock must be verified as Off. Read the Interlock value displayed in the Monitor » Inputs menu. If the 1313/1314 programmer indicates the interlock is On, review how you set the Interlock Type parameter (Drivers » Main Contactor Menu) and turn the interlock off.

Quick Links:
Brake Type parameter p.48
Brake (pot) wiring, p.20–23
Monitor/Inputs p.70
Pot2 Raw
Mapped Brake

The Brake Type parameter must be set to match the type of brake throttle (1, 2, 3, 5) and wiring. Next, adjust the Brake Deadband and Brake Max parameters to match the range of the brake pot. The Brake Pot value (Pot2 Raw) displayed in the Monitor » Inputs menu is useful when setting up these parameters. Read the displayed brake pot voltage at the point when the brake moves out of neutral and at the point just before full brake. Enter in these values for the deadband and max parameter settings. Then set up the other parameters in the Brake Menu as required by the applications.

Verify that that the brake settings are correct by checking the Mapped Brake value displayed in the Monitor » Inputs menu over the entire range of brake pot movement. The value displayed for Mapped Brake should be = 0% through the range of brake pot motion that is considered neutral. The displayed Mapped Brake should be = 100% through the range of motion that is considered maximum brake.

Contact your Curtis distributor or support engineer to resolve any issues about the brake setup before continuing with the setup procedure.

Step 8: Motor Technology & Feedback Type (see pages 55 and 59)

Set the Motor Technology parameter to match the motor used in your application (0 = ACIM, 1 = SPM).

Set the Motor Feedback Type parameter based on the Motor Technology setting:

Feedback Type = 1 (quadrature position encoder) for ACIM,
Feedback Type = 2 (Sin/Cos sensor) for SPM.

Make sure that the Feedback Type matches the feedback device used on the motor, and that you are using the right type of device for your motor. If there is not a match, stop the setup procedure until a compatible motor and feedback device are obtained and installed.

If your application uses an ACIM motor (which must use a quadrature encoder), program the Encoder Steps parameter to the correct setting. This information is typically available from the motor manufacturer. If the ACIM Characterization Procedure is used (Chapter 8A), it can determine the encoder steps, but only for encoders with 32, 48, 64, or 80 pulses per revolution (ppr).

⚠ **WARNING** **Setting the Encoder Steps parameter improperly may cause vehicle malfunction, including uncommanded drive.**

If your application uses an SPM motor (which must use a Sin/Cos sensor), the Sin/Cos min and max voltages will be learned during the SPM Characterization Procedure (Chapter 8B).

Step 9: Faults (see Chapter 11)

Cycle KSI (to clear any parameter change faults) and use the programmer to check for faults in the controller. All faults and errors (including those in the History file) must be cleared before continuing with the initial setup. Use Chapter 10 for help in troubleshooting. Contact your Curtis customer support engineer to resolve any fault issues before continuing with the setup procedure.

Step 10: Setting Feedback Direction (see page 59)

ACIM:

Quick Links:
Monitor/Inputs Menu p.70
Monitor/Motor Menu p.73

With the vehicle drive wheels still jacked up, no faults present in the controller, the interlock Off (as verified in the Monitor » Inputs menu), and both the throttle and brake in neutral (Mapped Throttle = 0% and Mapped Brake = 0% in the Monitor » Inputs menu), the encoder direction can be checked. Use the Monitor » Motor menu to view the Motor RPM display. Turn the motor by hand and observe the sign of Motor RPM. Positive is forward and negative is reverse. If you get a positive Motor RPM when you rotate the motor in the forward direction, and a negative Motor RPM when you rotate the motor in the reverse direction, the Swap Feedback Direction parameter is correct and should not be changed. If you are getting negative Motor RPM when rotating the motor forward, the Swap Feedback Direction parameter must be changed. Cycle KSI power and repeat the procedure until you are satisfied that the Swap Feedback Direction setting is correctly set. If the vehicle will use the emergency reverse feature, the reverse direction (negative Motor RPM) must be correctly selected so that when the Emergency reverse input is active the motor will rotate in the reverse direction. Contact your Curtis distributor or support engineer to resolve any issues about encoder direction or emergency reverse before continuing with the setup procedure.

SPM:

Step 10 is not applicable to SPM motors. Go to the next step for SPM motor in-vehicle auto-characterization.

Step 11: Motor Characterization

If your motor is an ACIM motor, you must either:

(a) Already have software with the motor data programmed to match your motor. The pre-set motor data software is usually the result of contacting your Curtis distributor or support engineer and getting a match between your motor and the Curtis ACIM motor database, or by shipping a motor to Curtis for dyno characterization.

or (b) Use the in-vehicle ACIM Motor Characterization Procedure (Chapter 8A). This procedure will set the direction, may set the Encoder Steps, learn ACIM motor data, and set the FW Base Speed and Field Weakening Drive.

Quick Links:
ACIM characterization p.85–90
SPM characterization p.91–92

If your motor is an SPM motor, you must use the in-vehicle SPM Motor Characterization Procedure (Chapter 8B). This procedure will determine the number of motor poles, set the direction and the Sin/Cos sensor parameters, and learn the SPM motor data parameters.

After ensuring that the controller has the motor data values that match your system, complete Steps 12 through 14 of the initial setup.

⚠ WARNING **NOTE: Do not take the vehicle down off the blocks if you will be re-running the Motor Characterization procedure.**

Step 12: Checking Direction of Rotation

Do not take the vehicle down off the blocks until the motor is responding properly.

Only after the motor is responding properly is it safe to lower the vehicle and place the drive wheels on the ground.

Once the encoder direction set correctly, this step tests to see whether the motor rotation is correct. Begin by cycling KSI off and on (to clear any parameter change faults), then use the 1313/1314 programmer to check for faults in the controller. All faults must be cleared before continuing with the setup procedure. Apply the interlock input and verify that Interlock = On (as verified in the Monitor » Inputs menu). Then, while keeping the brake in neutral*, select a direction and apply throttle. The motor should begin to turn.

For an ACIM motor, observe the motor rotation and if the motor appears to be "fighting itself" (struggling at full current while jerkily turning at very low speed), change the setting of the Swap Two Phases parameter.

For an SPM motor, observe the motor rotation and if it is turning in the wrong direction repeat the SPM auto-characterization procedure, where the direction is set in its step 11.

Contact your Curtis distributor or support engineer if the proper motor direction cannot be resolved.

Step 13: Emergency reverse (see page 65)

Set up the parameters in the Emergency Reverse Menu. Note: Emergency Reverse is active only if you are using Speed Mode Express or Speed Mode as your motor tuning mode.

Step 14: Interlock Braking (see page 66)

Set up the parameters in the Interlock Braking Menu.

---

*Note: The Throttle Command is zeroed if the Brake Command is > 0 for Control Modes 0 and 1. See Figure 16, page 108.

8A — AUTOMATED ACIM MOTOR CHARACTERIZATION PROCEDURE

⚠ WARNING **Motor will rotate during this procedure. Do not take the vehicle down off the blocks.**

This procedure is only for applications using an ACIM motor and quadrature encoder.

The procedure is performed in two parts. Both parts must be completed for proper controller setup. The first part applies to all systems, and the second part is different for traction systems and hydraulic systems. It is assumed that Initial Setup steps 1 through 10 have been completed.

The procedure assumes the motor is approximately room temperature (20–25°C); do not characterize a hot motor without a temperature sensor.

If characterizing a traction system, the vehicle should have its drive wheels clearly off ground, and the vehicle should be safely blocked from accidental movement. The drive wheels should be freely spinning—any dragging brake or excessive friction may invalidate this test, or cause it to fail.

If characterizing a hydraulic system, the motor must be unbolted from the hydraulic pump and allowed to spin freely. The test will not work properly if the motor is left connected to the pump. Note: The motor may spin to high speed in either direction.

Hint: The procedure is easier to conduct if you add the various motor Parameter (Program) and Monitor variables to your 1313's Favorites folder. The 1314 programmer can also be used, although it does not offer the convenience of the Favorites folder.

PART 1: TRACTION AND HYDRAULIC SYSTEMS

1. Verify that Motor Technology = 0-ACIM and Feedback Type = 1-encoder. This configuration, and these settings, are required to run this procedure.
   Motor » Control Algorithms » 0-ACIM
   Motor » Feedback Options » Feedback Type » 1-Encoder
2. Enter the number of motor poles in the Motor Poles parameter. The vast majority of induction motors will have 4 poles.
   Motor » Control Algorithms » 0-ACIM » Characterization Tests » Motor Poles
3. Enter the desired Max Test Speed for the characterization test. Note this speed might not be achieved, depending on system characteristics; this is normal. A typical setting is approximately 1/3 of the maximum motor speed in the application.
   Motor » Control Algorithms » 0-ACIM » Characterization Tests » Max Test Speed
4. Enter the desired Max Test Current for the characterization test. A typical setting is 70% (70% of the maximum motor or controller rating, whichever is higher). Generally this is only reduced if motor heating during the test is a problem, or resonance in the motor occurs at high currents.
   Motor » Control Algorithms » 0-ACIM » Characterization Tests » Max Test Current.
5. Using the 1313/1314, clear the Fault History (Faults » Clear Fault History).
6. Ensure that Interlock is enabled (Monitor » Inputs » Interlock).
7. Set Test Enable = 1.
   Motor » Control Algorithms » 0-ACIM » Characterization Tests » Test Enable
8. If any faults are present, stop and resolve the issue before continuing.
9. Note that no cutbacks should be in effect (thermal, voltage, etc.) when these tests are run. Also, the power limiting maps should not cut back current over the characterization speed

Quick Links:
Motor Parameters
  Control Algorithms p.55
  Characterization Tests p.55
  Feedback Options p.59
Power Limiting Map p.43
Monitor
  Inputs/Interlock p.70

range. Check and verify that the power limiting map parameters are set to 100% over the characterization speed range.

Current Limits » Power Limiting Map

⚠ WARNING **Motor will start to rotate after next step.**

Quick Links:
Power Limiting Map p.43
Characterization Tests p.55
Test Throttle
Motor Characterization Error p.75

10. Set Test Throttle = +1.

    Motor » Control Algorithms » 0-ACIM » Characterization Tests » Test Throttle

11. After approximately 30 or more seconds the motor will begin to rotate. It is critical to verify the motor is turning in the FORWARD vehicle direction. If it is not, set Test Throttle = 0, wait for the motor to come to a stop, then set Test Throttle = –1.

    Notes: (1) This step runs faster if TACT is not running. (2) If the motor starts to accelerate then slows down again, you may need to increase **Max Test Current** (IM_AutoChar_Max_Test_Current). See step 4 above.

12. The automated test may take several minutes. When it is complete, the controller will have a Parameter Change Fault. This is normal. Check whether other faults are present. If you have a Characterization Error fault, read the number at Monitor » Controller » Motor Characterization Error and reference the following table. All errors except "1" indicate the motor characterization data is invalid. For error "1," the data is valid but Encoder Steps must be set manually. Contact your Curtis distributor or support engineer if the Motor Characterization Errors indicated cannot be resolved.

Motor Characterization Errors	
0	Sequencing error. Normally caused by turning off Motor Characterization Test. Enable before running test.
1	Encoder signal seen but step size could not be auto-detected; set up Encoder Steps manually. (Only encoder steps of 32, 48, 64, and 80 will be identified automatically.) *Program » Motor » Encoder Steps (page 59).*
2	Motor temperature sensor fault.
3	Motor temperature > MotorTemp_Hot (150°C is the typical default). This is active only when the motor temp sensor is present and enabled.
4	Controller overtemperature.
5	Controller undertemperature.
6	Battery undervoltage.
7	Battery severe overvoltage.
8	Encoder signal not seen, or one or both channels missing.
9	Motor parameter out of characterization range; check to be sure motor has no load.

13. Cycle KSI power. The motor control should now be operational, though likely poorly optimized. The Slip Gain test is very important for most, but not all, motors; you won't know which until you perform the test and get the result. The following steps will complete the optimization process.

PART 2A: TRACTION SYSTEMS ONLY

Quick Links:
SlipGain p.55

14. Run the **SlipGain** test.

    Adjust the SlipGain parameter to provide maximum torque at stall (0 rpm motor speed). Note: The present SlipGain value was determined by the auto-characterization procedure, and is not the default value.

    Motor » Control Algorithms » 0-ACIM » Characterization Tests » SlipGain

    To determine the SlipGain setting, use either of the following two methods, with (a) being the most accurate:

Quick Links:
SlipGain p.55
Fault Detection Enable p.60
Express Mode p.31
  Accel Rate
Speed Mode p.35
  Full Accel HS
  Full Accel LS
  Low Accel Rate
Torque Mode p.40
  Accel Rate

Capture Speed 1 p.64
Time to Speed 1 p.77

(a) Configure the vehicle to measure stall torque, by using a load cell / draw bar test. Note: You will want to perform this test quickly to avoid excessive motor heating and provide the most accurate results.

Turn off encoder fault detection (Motor » Encoder Fault Setup » Fault Detection Enable).

While applying and holding full throttle, adjust SlipGain until you measure peak torque.

If you want to have encoder fault detection active (recommended), turn it back on.

(b) Alternately, the vehicle can be used as the "draw bar test" by accelerating the motor to a predetermined speed (rpm)—with the quickest time corresponding to the optimum SlipGain. This method uses the controller's time-to-speed function. The test-acceleration will be at full controller current.

Begin by setting the corresponding Accel Rates to very fast values, based upon the application's Control Mode.

Speed Mode Express: Accel Rate.
Speed Mode: Full Accel LS, Full Accel HS, Low Accel.
Torque Mode: Accel Rate.

On the 1313 programmer, add these two items to the Favorites shortcut, to easily toggle between them:

Monitor » Vehicle » Capture Speed 1
Monitor » Vehicle » Time to Speed 1
Parameters (Program) » Motor Control Tuning » 0-ACIM » Characterization Tests » SlipGain.

Next, set the **Capture Speed 1** parameter to an rpm enveloping the motor's desired maximum torque range. The monitor item, **Time to Speed 1**, will record the time taken for the vehicle (motor) to go from zero rpm to the programed Capture Speed 1 during its most recent acceleration.

To perform the test, from a stop, accelerate the vehicle through the predetermined speed. The timer starts counting when full throttle is applied, and stops counting when the speed is reached. A built-in trigger will allow the test to begin again once the vehicle comes to a stop and the throttle is re-engaged, so be sure to note the value of the test first before accelerating-away in subsequent runs. Each time, adjust the SlipGain value until the Time to Speed 1 is minimized.

This test should be run repeatedly over the same stretch of flat or uphill ground. Loading the vehicle will improve results, the idea being to have the motor produce maximum torque as in the draw-bar method. Work quickly, to avoid excessive motor heating, to obtain the most accurate results.

15. Run the **FW Base Speed** test.

Quick Links:
Drive_Current_Limit p.43
PL_Drive_Nominal p.44
FW Base Speed p.56
Base Speed Captured p.76

Set the FW Base Speed to 6000 rpm. The test should be run with batteries that have a reasonable charge.

Motor » Control Algorithms » 0-ACIM » Field Weakening Control » FW Base Speed

Set the Accel Rates to be very fast, so that you'll be accelerating at full current during the test. From a stop, quickly apply full throttle to accelerate to a high speed. After the motor settles at a speed for a moment, release the throttle to stop the test run. Note the value of the Base Speed Captured (Monitor » Controller » Motor Tuning » Base Speed Captured), and enter this value for the FW Base Speed setting.

Note:

- The base speed capture test restarts each time the vehicle comes to a stop and the throttle is released, so be sure to note the value before driving (accelerating) away.
- **This FW Base Speed parameter not only needs to be set during initial setup, yet reset each time the Motor Type or the low speed current limit is changed.** For example, if you lower Drive_Current_Limit or PL_Drive_Nominal, retest and reset this parameter.

16. Run the **Field Weakening** test.

    This test will enable you to decide between a more efficient (less torque) or more torque (less efficient) operation above the base speed, by adjusting the **Field Weakening Drive** parameter.

    Note: the present Field Weakening Drive value (0%) was determined by the above auto-characterization routine, and is not the default value (100%) in the native OS intended for the Curtis dynamometer characterized motors when a motor type (number) is utilized. The differences are:

    Auto Characterized: Field Weakening Drive is adjusted UP from 0% to the max Field Weakening Drive determined in this text.
    Dyno Characterized: Field Weakening Drive is adjusted DOWN from 100% (can be set from 0–100%)

    Increasing this parameter toward 100% will progressively allow more torque (along with more current) at high motor speeds, but increasing it too much will actually reduce torque while still driving a great deal of current. The auto-characterization value of 0% will give the most efficient motor operation, but will not give the highest torque at high speeds.

    If more torque is required at high speeds, run this Field Weakening Drive test.

    On the 1313 programmer, add these two items to the Favorites shortcut, along with Field Weakening Drive parameter, so you can easily toggle between them:

    Parameters (Program) » Motor » Control Algorithms » 0-ACIM » Field Weakening Control » Field Weakening Drive

    Parameters (Program) » Vehicle » Capture Speed 1, 2

    Monitor » Vehicle » Time Between Speeds

    Quick Links:
    Max Speed
    Express Mode p.31
    Speed Mode p.32
    Torque Mode p.39
    Capture Speed 1,2 p.64
    Field Weakening Drive p.56

    Time Between Speeds p.77

    Set **Capture Speed 1 and 2** to values that are close to the Max Speed setting. The Capture Speed 1 and 2 values MUST be set higher than the measured FW Base Speed in step 15 (because Field Weakening only affects performance at speeds above the "base speed"). Ideally the Capture Speed 1, 2 values should be above the second corner point of the motor torque – speed curve. For example, if the Max Speed is set to 4000 rpm, set Capture Speed 1 = 3500 rpm and Capture Speed 2 = 3800 rpm:

    Parameters (Program) » Speed Mode Express » Max Speed

    Parameters (Program) » Speed Mode » Speed Controller » Max Speed

    Parameters (Program) » Torque Mode » Speed Limiter » Max Speed

    From a stop, apply full throttle to accelerate to a speed greater than Capture Speed 2. Note the value displayed in Monitor » Vehicle » Time Between Speeds.

    Now increase the Field Weakening Drive setting and repeat the acceleration in the same direction, with the same load, and with the same full throttle and again note the Time Between Speeds value.

    Keep adjusting the Field Weakening Drive value and repeating the test until you find the Field Weakening Drive value that results in the smallest Time Between Speeds. This Field Weakening Drive value should be used for applications that require the most torque at high speeds.

    Some Field Weakening Drive settings may result in a test acceleration run where Capture Speed 2 cannot be obtained. These Field Weakening Drive settings cannot provide enough torque to get the vehicle past Capture Speed 2, and thus can be ignored.

    Use the Field Weakening Drive setting that best matches the application. It will be somewhere between 0% (most efficient, least motor heating) and the setting found in this test (highest torque at high speeds).

    NOTE: The Field Weakening Drive setting will have no effect at motor speeds below FW Base Speed.

17. Return to Chapter 6 and complete Initial Setup Steps 12 through 14.

Quick Links:
SlipGain p.55

Max Speed
  Express Mode p.31
  Speed Mode p.32

Current (RMS) p.74

PART 2B: HYDRAULIC SYSTEMS ONLY

14. Run the **SlipGain** test.

Adjust the **SlipGain** parameter to provide maximum torque at low speeds. Note: The present SlipGain value was determined by the auto-characterization procedure, and is not the default value.

On the 1313 programmer, add the motor current to the items in the Favorites shortcut, to easily toggle between them:

Monitor » Controller » Current (RMS)

Parameters (Program) » Motor Control Tuning » 0-ACIM » Characterization Tests » SlipGain.

Set Max Speed to a fairly low speed (but high enough to be able to lift a heavy load on the forks), typically 800 rpm. The Max Speed setting must be below the motor base speed, which is measured in the next step.

Put a very heavy load on the forks, preferable a max load.

Apply full throttle, and adjust the SlipGain parameter until the motor current is minimized. If the vehicle has a multistage mast, work in the first stage only so that the load is consistent.

This will be the SlipGain parameter value, unless following step 15, the base speed used here (e.g., 800 rpm) was too high.

Quick Links:
FW Base Speed p.56
Express Mode p.31
  Accel Rate
Speed Mode p.35
  Full Accel HS
  Full Accel LS
  Low Accel Rate
Test Field Current p.76
Min Field Current p.57
Base Speed Captured p.76

15. Run the **FW Base Speed** test.

Note: For this test, because the hydraulic motor (disconnected from the pump) can quickly accelerate past the “Base Speed”, it will be necessary to pre-flux the motor current prior to running this test to get an accurate measure of base speed. Since the controller will be running current with no throttle, ensure this test’s 1313 Favorites items are loaded so the test continues without delay to prevent motor and controller heating. Then, be sure to to re-set the controller to cancel the pre-flux following the test. This test is for hydraulic (pump) motor working in Speed Mode only. Run this test with batteries that have a reasonable charge.

Set in the 1313 Favorites

Parameters (program) » Motor » Control Algorithms » 0-ACIM » Field Weakening Control » FW Base Speed

Parameters (Program) » Motor » Control Algorithms » 0-ACIM » Field Weakening Control » Min Field Current

Monitor » Controller » Motor Tuning » Test Field Current

Monitor » Controller » Motor Tuning » Base Speed Captured

Set the Max Speed to 6000 rpm (i.e., beyond the maximum desired pump speed).

Set the Accel rates to be very fast, so the motor will be accelerating at full current during the test. Use only Speed Speed Modes for hydraulic systems.

Record the value of the Test Field Current (Monitor) and enter this value for the Min Field Current parameter.

⚠ CAUTION

The controller is now running current with no throttle, so continue this test without delay to prevent motor and controller heating.

From a stop, quickly apply full throttle to accelerate to a high speed. After the motor settles at a speed for a moment, release the throttle to stop the test. Note the value of the Base Speed Captured and enter this value for the FW Base Speed parameter setting.

⚠ WARNING

When this test is finished, you must re-set the parameter Min Field Current = 0 Amps to cancel the pre-flux current. Verify that the pre-flux current is canceled before continuing.

16. Run the Field Weakening test.

    This test will enable you to decide between a more efficient (less torque) or more torque (less efficient) operation at high speeds, by adjusting the hydraulic motor's Field Weakening Drive parameter. While the most efficient operation will occur with field weakening at the 0% auto-characterization value, more torque at high speeds may be required, necessitating adjusting the field weakening. Field Weakening Drive should be set just high enough to meet the high speed performance specifications, typically maximum lift speed with full load.

    Note: the present Field Weakening Drive value (0%) was determined by the above auto-characterization routine, and is not the default value (100%) in the native OS intended for the Curtis dynamometer characterized motors when a motor type (number) is utilized. The differences are:

    Auto Characterized: Field Weakening Drive is adjusted UP from 0% to the max Field Weakening Drive determined in this test.

    Dyno Characterized: Field Weakening Drive is adjusted DOWN from 100% (can be set from 0–100%)

Quick Links:
Motor RPM p.76
Field Weakening Drive p.56
Max Speed
    Express Mode p.31
    Speed Mode p.32

    Increasing the Field Weakening Drive parameter toward 100% will progressively allow more torque (along with more current) at high motor speeds, but increasing it too much will actually reduce performance while still driving a great deal of current.

    On the 1313 programmer, add these two items to the Favorites shortcut so you can easily toggle between them:

    Monitor » Controller » Motor Tuning » Motor RPM

    Parameter (Program) » Motor » Control Algorithms » 0-ACIM » Field Weakening Control » Field Weakening Drive.

    Run this test with no load on the forks. Work with only the first stage of a multistage mast. Work quickly to avoid overheating the controller or motor.

    Using the application's Speed (control) Mode, set the Max Speed parameter to a high speed that likely cannot be achieved by the hydraulic system.

    Set Field Weakening Drive = 100% (note: this test work works DOWN from 100% to find the actual maximum value).

    Apply full throttle, running the motor towards the maximum speed. Record the maximum (achieved) Motor RPM.

    Repeat the acceleration runs while continuing to lower the Field Weakening Drive value before on each run until you notice the achievable maximum motor speed fall off significantly (20–30 rpm). This number represents the **maximum** Field Weakening Drive value (%) to achieve the maximum torque/speed envelope of the hydraulic motor (do not use a higher percentage). You can always reduce the Field Weakening Drive percentage to reduce energy consumption and improve efficiency (but reducing torque output) at high speeds.

    NOTE: The Field Weakening Drive setting will have no effect at motor speeds below FW Base Speed.

17. Return to Chapter 6 and complete Initial Setup steps 12 through 14.

8B — AUTOMATED SPM MOTOR CHARACTERIZATION PROCEDURE

⚠ WARNING **Motor will rotate during this procedure. Do not take the vehicle down off the blocks.**

This procedure is only for applications using an SPM motor and Sin/Cos sensor.

This procedure is performed in one stage and takes approximately 5–10 minutes. It can only be used on a sinusoidal wound SPM motor with a Sin/Cos absolute position sensor (e.g, RLS RM22, SKF BX-BMB-7050, etc.) set up with one sensor revolution per mechanical revolution.

It is assumed that Initial Setup steps 1 through 9 have been completed and that the motor is approximately room temperature (20–25°C); do not characterize a hot motor without a temperature sensor.

If characterizing a traction system, the vehicle should have its drive wheels clearly off ground, and the vehicle should be safely blocked from accidental move-ment. The drive wheels should be freely spinning—any dragging brake or excessive friction may invalidate this test, or cause it to fail.

If characterizing a hydraulic system, the motor must be unbolted from the hydraulic pump and allowed to spin freely. The test will not work properly if the motor is left connected to the pump. Note: The motor will spin to Max Test Speed in both directions.

Quick Links:
Motor Technology p.55
Feedback Type p.59
 Sin/Cos p.60
Characterization Tests p.59
 Test Enable
 Test Throttle
 Max Test Speed
 Max Test Current

Interlock (monitor) p.70

1. Verify that Motor Technology = 1-SPM and Feedback Type = 2-Sin/Cos sensor. This configuration, and these settings, are required to run this procedure.

   Motor » Control Algorithms » 1-SPM

   Motor » Feedback Options » Feedback Type » 2-Sin/Cos

2. Enter the maximum speed the motor is intended to turn as the Max Test Speed for the characterization test. Note this speed might not be achieved, depending on system characteristics; this is normal. A typical setting is 5000 rpm, but clearly the Max Test Speed should not be set to a higher speed than safe for the mechanical configuration.

   Motor » Control Algorithms » 1-SPM » Characterization Tests » Max Test Speed

3. Enter the desired Max Test Current for the characterization test. A typical setting is 20% (note this is 20% of the maximum controller rating). Generally this is only reduced if motor heating during the test is a problem. Generally this is only increased if the motor fails to rotate during commissioning.

   Motor » Control Algorithms » 1-SPM » Characterization Tests » Max Test Current

4. Using the 1313/1314, clear Fault History (Faults » Clear Fault History).

5. Enable the SPM (PMAC) Auto Characterization by setting **Test Enable = 1**.

   Motor » Control Algorithms » 1-SPM » Characterization Tests » Test Enable

6. Turn on (enable) Interlock (Monitor » Inputs » Interlock).

7. If any faults are present, stop and resolve the issue before continuing.

8. Set **Test Throttle = +1**.

   Motor » Control Algorithms » 1-SPM » Characterization Tests » Test Throttle

⚠ WARNING **Motor will start to rotate in step 9 and faster in step 10.**

9. The controller will start to inject test pulses. After a few minutes (when pulsing stops), the motor will begin to rotate very slowly. **It is critical to verify the motor is turning in the FORWARD vehicle direction**. If it is not, set Test Throttle = 0, wait for the motor to come to a stop, then set Test Throttle = –1. The motor will start again in the same direction. The controller will properly set the direction at the end of characterization process. (Note: This is a different operation than that in the ACIM characterization procedure, which does turn the motor in the other direction when Test Throttle is set negative.)
10. After about a minute, the motor will spin up to a moderate speed, then to high speed (limited by Max Test Speed) in each direction.
11. When the automated test is complete, the controller will have a Parameter Change Fault. This is normal. Check whether other faults are present. If you have a Characterization Error fault, read the number at Monitor » Controller » Motor Characterization Error and reference the following table. An error during the SPM test indicates the motor characterization data is invalid; contact your Curtis distributor or support engineer for assistance if the indicated error cannot be resolved.

Quick Links:
Motor Characterization Errors p.75

Motor Characterization Errors	
0	Sequencing error. Normally caused by turning off Motor Characterization Test. Enable before running test.
2	Motor temperature sensor fault.
3	Motor overtemperature >150°C (active only when temp sensor is present).
4	Controller overtemperature.
5	Controller undertemperature.
6	Battery undervoltage.
7	Battery severe overvoltage.
9	Motor parameter out of characterization range; check to be sure motor has no load.
20	Sin/Cos sensor not found.
21	Phasing not detected (check to be sure the motor has no load).
22	Sin/Cos sensor characterization failure.
23	Started motor characterization while motor rotating.

12. Cycle KSI power.
13. Return to Chapter 6 and complete Initial Setup Steps 12 through 14.

9 — TUNING GUIDE

Many aspects of vehicle performance can be optimized, using the wide variety of adjustable parameters available to these E and SE controllers. Once a vehicle/motor/controller combination has been tuned, the parameter values can be made standard for the system or vehicle model. Any changes in the motor, the vehicle drive system, or the controller will require that the system be tuned again to provide optimum performance.

Selecting the Control Mode (see page 31)

Before starting to tune your vehicle's performance, you must select which control mode you use. Set the Control Mode Select parameter = 0 (Speed Mode Express for either traction or pump motors), = 1 (Speed Mode, for either traction or pump motors) or = 2 (Torque Mode, for traction motors). Cycle KSI input Off and then On (to clear any parameter change faults) and use the 1313 handheld or 1314 PC programmer to check for faults in the controller. Then proceed to the tuning steps for the control mode you have selected.

Conduct the steps in the sequence given, because successive steps build upon the ones before. It is important that the effect of these programmable parameters be understood in order to take full advantage of the controller's powerful features. Please refer to the descriptions of the applicable parameters in Chapter 4 if there is any question about what any of them do.

0 – Speed Mode Express Tuning (see page 31)

Speed Mode Express is the same as Speed Mode with the exception that it has fewer parameters and is therefore simpler to use. Most vehicle applications will find success with Speed Mode Express; however, for some applications vehicle performance cannot be satisfactorily fine-tuned in Speed Mode Express. In this case, change your control mode to Speed Mode (i.e., set Control Mode Select =1).

a. For traction applications, set Pump Enable to Off. For AC pump applications, set this parameter On.

b. Adjust Max Speed to the maximum speed the motor should turn in the vehicle application; this speed setting corresponds to an input of full throttle.

c. Adjust Typical Max Speed to the approximate maximum speed that the motor will spin. This is usually the same value as the setting for Max Speed, but some applications have a Max_Speed_SpdMx that changes (in the VCL software). If the Max_Speed_SpdMx changes, set Typical Max Speed to the highest speed the motor is expected to reach. This value does not need to be set precisely since it will not change motor performance. Typical Max Speed sets a reference point for the "rate" parameters (accel, decel, brake rates), so that applications that have a changing Max_Speed_SpdMx will not experience changes in the rates (because the rates are referenced to the unchanging Typical Max Speed value). Once you set the Typical Max Speed parameter you should not readjust it without adjusting all the rate parameters as well.

d. Kp and Ki typically do not need to be changed as the default values will work well in most applications. If you want to adjust Kp (for looser or tighter following of the speed trajectory set by the accel, decel, and brake rates), follow the procedure in step "d" in the Speed Mode tuning section.

e. Adjust the Accel Rate and Decel Rate as necessary while moving the throttle to different positions (i.e., neutral to full throttle, half throttle to full throttle, full throttle to half throttle, full throttle to neutral, neutral to low throttle, etc.). For AC pump applications, typically the Accel Rate and Decel Rate are set very fast for quick response to hydraulic inputs.

Quick Links:
Control Mode select p.31
Speed Mode Express menu p.31
    Max Speed
    Kp
    Ki
    Accel Rate
    Decel Rate
    Brake Rate
Typical Max Speed p.54

f. Adjust the Brake Rate as necessary while reversing the throttle input (i.e., full throttle forward to low throttle reverse, full throttle forward to full throttle reverse, full throttle reverse to low throttle forward, etc.). If a brake input is present in the application (Brake Pedal Enable = On) continue adjusting Brake Rate by applying different amounts of brake throttle (i.e., full throttle forward, then apply full brake or full throttle forward, then apply low brake, etc.). For AC pump applications the Brake Rate has no effect on performance since the AC pump will not run in reverse nor with a brake input.

⚠ WARNING

AC pump motor applications, which in step "a" had the Pump Enable parameter set to On, may also be controlling hydraulic valves (load hold valve, proportional valve). The Proportional Driver parameters (page 53) and some VCL will typically be used to set up the control of these valve driver outputs. Consult with your Curtis distributor or support engineer regarding hydraulic valve control.

1 – Speed Mode Tuning (see pages 32–39)

a. For traction applications, set Pump Enable to Off. For AC pump applications set this parameter On.

b. Adjust Max Speed to the maximum speed the motor should turn in the vehicle application; this speed setting corresponds to an input of full throttle.

c. Adjust the Typical Max Speed to the approximate maximum speed that the motor will spin. This is usually the same value as the setting for Max Speed, but some applications have a Max_Speed_SpdM that changes (in the VCL software). If the Max_Speed_SpdM changes, set the Typical Max Speed to the highest speed the motor is expected to reach. This value does not need to be set precisely since it will not change motor performance. Typical Max Speed sets a reference point for the "rate" parameters (accel, decel, brake rates), so that applications that have a changing Max_Speed_SpdM will not experience changes in the rates (because the rates are referenced to the unchanging Typical Max Speed value). Once you set the Typical Max Speed parameter you should not readjust it without adjusting all the rate parameters as well.

d. Kp and Ki (LS & HS) typically do not need to be changed as the default values work well in most applications. These parameters control how tightly the actual motor speed will track the requested speed trajectory (speed trajectory is set by the Accel, Decel, and Brake rates).

Quick Links:

- *Control Mode select* p.31
- *Speed Mode menu* p.32
    - *Speed Controller menu* p.32
        - *Max Speed*
        - *Kp*
        - *Ki (LS/HS)*
    - *Response menu* p.35
        - *Accel Rate*
        - *Decel Rate*
        - *Brake Rate*
    - *Restraint menu* p.37
        - *Soft Stop Speed*
            - *Position Hold menu* p.38
- *EM Brake Control menu* p.49
- *Typical Max Speed* p.54

If you want to adjust the Kp (for looser or tighter following of the speed trajectory), follow these guidelines.

- Set the following parameters. Before setting them, make a note of their present (default) settings so you can return them to these original values at the end of this procedure.
    - In the Speed Mode » Speed Controller menu, set the **Max Speed** to low value (≈1000 rpm), as high speed operation is not needed to observe system response.
    - In the Speed Mode » Response menu, set all the **Accel and Decel** rates to their fastest values (0.1 seconds); this allows better observation of the system response.
    - In the Speed Mode » Restraint menu, set the **Soft Stop Speed** parameter = 0 rpm to disable the soft stop speed function.
    - In Speed Mode » Restraint » Position Hold Menu, set **Position Hold Enable** = Off such that the position hold function will not interfere with the speed control gain setup procedure.
    - *If your vehicle has an EM Brake*, in the EM Brake menu, set the **EM Brake Type** = 1. This setting will release the EM Brake as soon as interlock is asserted.

- Cycle KSI to clear any faults. Then, assert (close) the Interlock.
- Using very quick, pulsing throttle movements, increase the throttle and then release it to 0%. The intent is to give the speed controller torque impulses.
- Increase Kp and repeat the throttle tests. Increase Kp until you start to notice marginal stability (normally motor bouncing, or continuous oscillation in the gears, is heard). Note: It is possible that very heavy vehicles will not experience marginal stability even at the highest setting of Kp.
- Once the Kp setting for marginal stability is found, reduce the Kp value by about one third (i.e., final Kp = marginal stability Kp * 2/3).
- If you will be using Speed Mode Express, enter this Kp value for the Kp parameter in the Speed Mode Express menu.
- Set the Max Speed, Accel/Decel, Soft Stop Speed, Position Hold, and Brake Type parameters back to their original values.

Quick Links:
Speed Mode menu p.32
Speed Controller menu p.32
Max Speed
Kp
Ki (LS/HS)
Response menu p.35
Accel Rate
Decel Rate
Brake Rate
Restraint menu p.37
Soft Stop Speed
Position Hold menu p.38

e. In the Speed Mode » Response menu, adjust the five Accel and Decel Rate parameters as necessary while moving the throttle to different positions (i.e., neutral to full throttle, half throttle to full throttle, full throttle to half throttle, full throttle to neutral, neutral to low throttle, etc.). For AC pump applications, these parameters are typically set very fast for quick response to hydraulic inputs.

f. In the Speed Mode » Response menu, adjust the remaining three brake rate parameters as necessary while reversing the throttle input (i.e., full throttle forward to low throttle reverse, full throttle forward to full throttle reverse, full throttle reverse to low throttle forward, etc.).

If a brake input is present in the application (Brake Pedal Enable = On) continue adjusting these three brake rates by applying different amounts of brake throttle (i.e., full throttle forward, then apply full brake or full throttle forward, then apply low brake, etc.).

For AC pump applications these parameters have no effect on performance since the AC pump will not run in reverse nor with a brake input.

g. The parameters in the Speed Mode » Response » Fine Tuning menu typically do not need to be changed as the default values work well in most applications.

⚠ WARNING

AC pump motor applications, which in step “a” had the Pump Enable parameter set to On, may also be controlling hydraulic valves (load hold valve, proportional valve). The Proportional Driver parameters (page 53) and some VCL will typically be used to set up the control of these valve driver outputs. Consult with your Curtis distributor or support engineer regarding hydraulic valve control.

2 – Torque Mode Tuning (see pages 39–42)

Quick Links:
Torque Mode/Speed Limiter p.39
Kp
Ki
Kd
Response menu p.40
Fine Tuning p.41
Figure 9 p.42
Current Limits menu p.43
Typical Max Speed p.54

a. Set Max Speed to the maximum speed you want to limit the motor to.

b. Kp, Ki, and Kd typically do not need to be changed as the default values will work well in most applications. These parameters control how tightly the controller limits the speed of the motor to the programmed Max Speed.

c. Set Typical Max Speed to the expected maximum speed of the motor.

d. Adjust the parameters shown in Figure 9 to set up the throttle mapping:

- Drive Current Limit (Current Limits menu)
- Regen Current Limit (Current Limits menu)
- Forward/Back Full Restraint Speed (Torque Mode » Response menu)
- Brake Taper Speed (Torque Mode » Response » Fine Tuning menu)
- Neutral Braking (Torque Mode » Response menu)
- Neutral Taper Speed (Torque Mode » Response menu)
- Creep Torque (Torque Mode » Response » Fine Tuning menu).

e. In the Torque Mode » Response menu, adjust the four accel, decel, and release rate parameters as necessary while moving the throttle to different positions (i.e., neutral to full throttle, half throttle to full throttle, full throttle to half throttle, full throttle to neutral, neutral to low throttle, etc.).

f. The other parameters in the Torque Mode » Response » Fine Tuning menu typically may need to be changed for some applications. Read the parameter descriptions and adjust as necessary.

10 — VEHICLE CONTROL LANGUAGE (VCL)

Curtis 1232E/34E/36E/38E and 1232SE/34SE/36SE/38SE controllers have a built-in programmable logic controller with application-specific functions. VCL (Vehicle Control Language) software provides a way to implement unique and complex vehicle control functions.

VCL is a simple programming language that will feel very familiar to anyone who has worked with BASIC, Pascal, or C. Working with VCL requires the installation of the WinVCL program onto a PC. WinVCL will compile VCL programs and flash download the software into the controller through the computer's serial port. The install process for WinVCL will also install three important manuals on your PC: the WinVCL User's Guide, VCL Programmer's Guide, and VCL Common Functions Manual. These manuals, which are in PDF format, include more detailed information about VCL than is included here.

This chapter of the manual summarizes VCL and also describes aspects and functions of VCL that are specific to these E and SE controllers. For a more complete understanding of the functions and capabilities of VCL, see the WinVCL User's Guide, VCL Programmer's Guide, and VCL Common Functions Manual.

Summary of VCL Basics

- VCL is not case-sensitive:
  put_pwm(), Put_PWM(), and PUT_PWM() are identical.
- Spaces in variable names are not allowed in VCL; use underscores in place of spaces.
  Example: Forward_Offset is the VCL name for the 1313/1314 parameter
  Forward Offset.
- Functions are followed by parentheses; for example:
  Reset_Controller() is a function
  Reset_Voltage is a variable.
- Logical statements must be inside parentheses; examples:
  IF (setpoint >50)
  ELSE IF ((setpoint <20) & (temperature >100)).
- Comments are preceded by semicolons.

The VCL functions described in the VCL Common Functions Manual are available to all 1232E/SE, 1234E/SE, 1236E/SE, and 1238E/SE controllers. These controllers have these additional specific functions, listed below. All VCL functions, common and specific, are also available in the controller's os31 SysInfo file.

VARIABLE TYPES

VCL provides dedicated space in which to store custom variables. There are four types of variables, based on their type of storage: volatile storage (RAM) and three types of non-volatile storage (EEPROM) are available.

RAM variables are stored only while power is on; they are lost at power-down. They must be initialized on power-up by explicit VCL assignments (i.e., User1 = 12).

NVUser1–15 EEPROM variables are 15 variables automatically saved at power-down and restored at power-on. During power-down or a power-failure (brownout), these variables are saved to NVM1. During operation, these variables are also periodically saved (every 6 minutes) to NVM2, thus two locations are used to preserve the data. At power-up, the data in NVM1 is read first, yet if it is corrupted, the data from NVM2 is restored. See the section on non-volatile memory access in the VCL Common Functions manual for more information, including caution to changing the NVM2 save rate, and rational of the save/restore strategy.

Block EEPROM are 38 blocks of 15 variables (total of 570 variables), which are stored and recalled using the functions NVM_Block_Read and NVM_Block_ Write. The 38 blocks are called NVM3–NVM40. The read and write functions must point to the RAM variables that the EEPROM blocks should be written from or read to. For example, NVM_Block_Read(NVM10,0,15,User20) will read the 15 variables stored in EEPROM block NVM10 and restore those variables to the 15 variables starting with RAM variable User20 (so the 15 EEPROM variables would be restored to User20–34). See the section on non-volatile memory access in the VCL Common Functions manual for more information.

Parameters EEPROM variables are a special type of EEPROM variable that is intended to be used to create OEM defined 1313/1314 programmer parameters. These parameters can be defined as 16-bit by using the P_User variables or they can be defined as bit (On/Off) by using the P_User_Bit variables. These variables are typically written to EEPROM through the 1313 handheld or 1314 PC programmer interface (i.e., when a user changes a parameter setting using the 1313). They can be used in the VCL code, but changing a P_User (or P_User_Bit) value with VCL will only change the variable value in RAM and will not change the value in EEPROM. Thus, these variables are intended for creating and defining 1313/1314 programmable parameters only.

VCL can modify the control mode parameters in RAM by using the VCL variable name for the programmable parameter. For example,

```
Brake_Rate_SpdMx = 3000 ;Change Brake Rate to 3.0sec
```

will change the RAM value of the Speed Mode Express's Brake Rate; the new value will be used in determining the braking rate. However, the value of the parameter's stored EE value remains unchanged; when the controller is turned off, the RAM value will be lost. The next time the controller is powered back on, the "old" value of Brake Rate will be restored from EE memory. To save this RAM value in VCL, you must use the NVM_Write_Parameter function ((i.e., NVM_Write_Parameter(Brake_Rate_SpdMx)).

Parameter values that are changed by using the 1313 handheld or 1314 PC programmer are saved directly to EE memory. The 1313/1314 changes will be retained and restored the next time the controller is powered back on.

The table below summaries the available VCL variables.

Type	Quantity	Range
RAM	420 variables	User1 – User120 AutoUser1 – AutoUser300
NVUser EEPROM	15 variables	NVUser1 – NVUser15
Block EEPROM	38 blocks (15 variable each)	NVM3 – NVM40
Parameters EEPROM	150 variables and 10 variables of 8 bits each (80 bits)	P_User1 – P_User150 P_User_Bit1 – P_User_Bit10

VCL RUNTIME RATES

VCL is an interpreted language. Each line of VCL code is converted (compiled) into a set of codes and then flash loaded into the controller. The controller interprets these codes one line at a time while the system is powered up. Here are the processing rates of the various functions:

Item	Function/Item Description	Quantity	Service Rate
ABS	Absolute Value	2	4 ms
ADC	Analog to Digital Converter Input (Analog1 and Analog2)	2	1 ms
CAN	CAN Communications	24	4 ms
CPY	Copy	8	4 ms
DLY	Delay	32	1 ms
FLT	Filter	4	1 ms
LIM	Limit	4	4 ms
MAP	Map	8	4 ms
MTD	Multiply then Divide	4	4 ms
NVM	Non-Volatile Memory block (NVM3-40)	38	2 ms
PID	Proportional Integral Derivative	2	4 ms
POT	Potentiometer Input	2	8 ms
PWM	Pulse Width Modulated output	6	4 ms
RMP	Ramp	4	1 ms
SCL	Scaling	8	4 ms
SEL	Selector, 2-position switch	8	4 ms
SEL_4P	Selector, 4-position switch	8	32 ms
SW	Switch Input	1*	4 ms
TMR	Timers (hourmeters)	3	1 ms

** There is only one Switch variable; it has 16 associated bit-variables.*

I/O CONTROL WITH VCL

Digital Inputs

The controllers each have 16 digital inputs. Nine are switch inputs (Sw_1 through Sw_8, and Sw_16. These switch inputs are shown on the standard wiring diagram (Figure 3, page 12). The remaining seven digital inputs are less obvious: one on each driver and digital output (Sw_9 through Sw_15). These can be used as digital inputs or to sense the state of the output or its wiring (e.g., open coil check).

To address a digital input in a VCL program, use the desired input label (Sw_1 through Sw_16). You must use On or Off in the code when determining a switch state; using true/false or 1/0 will give erroneous results.

```
if (Sw_1 = ON)
{
;put code here to run when switch 1 is On
}
if (Sw_16 = OFF)
{
;put code here to run when switch 16 is Off
}
```

All switch inputs are automatically debounced by the VCL operating system. This prevents noisy contacts or contact bounce from causing erroneous events in your VCL code. The debounce time can be varied from 0 to 32 ms in 4 ms steps, using this function:

```
Setup_Switches(5); 20 milliseconds
```

If this line is not in the VCL code, the debounce time is set at 16 ms.

Driver and Digital Outputs

There are five driver outputs (PWM1 through PWM5) and two digital outputs (DigOut6 and DigOut7). These outputs have variations in current and frequency range. For their specifications, see "digital and PWM outputs" on page 15.

Driver outputs have high current FET output stages and can be pulse width modulated (PWM) to vary the average output to inductive loads such as contactors and relays. This is useful when the battery voltage needs to be brought down for lower voltage coils. The two digital outputs are 1 A drivers that are only On or Off.

Drivers use a special VCL function to set their PWM level. This PWM level can be set up in a signal chain to update automatically or can be set directly in the main loop. PWM can be set from 0–100% using the digital range of 0 to 32767.

```
Put_PWM(PWM2,16384)
```

will output a 50% waveform on Driver 2.

```
Automate_PWM(PWM2,@user1)
```

will continually update the Driver 2 output with the present value of variable User1. This automate statement needs only to be run once, usually in the initialization section of the VCL program. VCL can monitor the present value of a PWM driver: the variable PWMx_Output (where "x" is the PWM channel number) is automatically filled with the present value of the driver output.

The proportional driver (Driver 5 , Pin 2) is different from Drivers 1–4. It can be controlled in two ways: with the proportional driver processing function (see Figure 17) or with the VCL Put_PWM() function. The VCL statement Put_PWM(PWM5, 16383) will result in a 50% PWM output on pin 2 only if the parameter PD Enable is set to Off. For more information about the proportional driver, see the section entitled "INTERFACING THE PROPORTIONAL CURRENT DRIVER" on page 109.

Control of the two digital outputs (Digital Outputs 6 and 7) is done using the VCL functions Set_Digout() and Clear_Digout().

```
Set_DigOut(DigOut6)
```

will set Digital Output 6 On (active). VCL can monitor the present value of a digital output driver: the bit variable Digx_Output (where "x" is the digital output channel number) is automatically filled with the present value of the driver output (On or Off).

It is important to note that all outputs are active Low. With 100% PWM or an output of "On," the FET or transistor will be pulling hard to ground. A DVM on the output will measure near 0 volts.

Potentiometer Inputs

These controllers have two potentiometer inputs, which are typically used for throttle and brake. Many features (mapping, acceleration rates, etc.) are built in as 1313/1314 programmer parameters. Still, there are times that these potentiometer inputs may be needed for other functions such as steering angle or height sensing, or simply as data inputs. The standard way to input pot information is to set the parameter Throttle Type (or Brake Type) to an appropriate value of 1–4 as described in the Throttle Type pages, and the Throttle and Brake parameter menus. When set to a value of 1–4, the resulting signal chain can operate without the use of any VCL.

However, if an OEM wishes to control the throttle (or brake) signal chain in VCL or use the throttle (or brake) inputs for signals that are not throttle (or brake) signals, then the parameter Throttle Type (or Brake Type) should be set to a value of 5. Setting the parameter Throttle Type (or Brake Type) to a value of 5 changes the routing of the appropriate signal chain (either throttle or brake) and allows the VCL programmer access to the Throttle Pot (or Brake Pot) output variables; see Figure 15.

Quick Links:
Throttle Type Selection p.20–23
Three-Wire p.21
Two-Wire p.20,23
One-Wire p.21
Figure 15 p.105
Figure 17 p.109
Throttle menu p.46
Brake menu p.48
Setup_Pot ( ) p.122

Using the Setup_Pot() function, executed at the beginning of a VCL program, will define the potentiometer input connection(s) as THREE_WIRE (uses Pot High and Pot Low connections), TWO_ WIRE (variable resistor, or rheostat, uses Pot Low but no connection to Pot High), or ONE_WIRE (a voltage input, no connection to either Pot High or Pot Low).

THREE_WIRE potentiometer connections are the same as the 3-wire potentiometer connections shown in Figure 5 for Throttle Type 2.

TWO_WIRE potentiometer connections are the same as the 2-wire potentiometer connections shown in Figure 4 for Throttle Type 1.

ONE_WIRE potentiometer connections are the same as the Voltage Source or Current Source connections shown in Figure 5 for Throttle Type 2.

Note that the Setup_Pot() function will only work (and is only needed) if the corresponding Type is set to 5 (Throttle Type = 5 or Brake Type = 5).

```
Setup_Pot(THROTTLE_POT,THREE_WIRE)
```

will set up the throttle pot input for wiring using all three connections (pins 15, 16, 18).

To set up the brake pot input for use in VCL, use the Brake_Pot constant in place of the Thottle_Pot constant in the Setup_Pot function.

```
Setup_Pot(BRAKE_POT,TWO_WIRE)
```

will set up the brake pot input for wiring using two connections (pins 17, 18).

The 0–100% position of the potentiometer is represented by a value from 0–32767 in VCL, and is set up through the VCL Setup_Pot() function. It is important to use the correct setup (ONE_WIRE, TWO_WIRE, or THREE_WIRE) since the input is automatically re-scaled for 0–100% based on the wiring used; for example, the voltage at the Pot Low pin is automatically subtracted and re-scaled on a THREE_WIRE pot.

Another effect of setting the Throttle Type = 5 is that the signal chain for the throttle now gets its input from a different source. The input to the throttle chain is now a VCL variable called VCL_Throttle instead of the throttle pot. Similarly, Brake Type = 5 means the brake signal chain will get its input from a VCL variable called VCL_Brake rather than from the brake pot. The VCL_Throttle and VCL_Brake variables will need to be controlled in the VCL program.

One of the unique features of the potentiometer inputs (as opposed to the analog inputs) is that they have automatic pot fault detection functions running in the motor controller OS. The VCL programmer has access to the pot detection functions with the Setup_Pot_Faults() function. With this function, VCL can re-set the high and low thresholds at which a fault occurs. This function also forces the pot value to a definable level if a fault occurs. Note that the Setup_Pot_Faults() function will work for all throttle Types (1–5). See page 123 for more detail on this function, and **Interfacing the Throttle and Brake Commands** (below) for further information on both the Throttle and Brake processing..

Analog Inputs

These controllers have two generic analog inputs (pins 24 and 8). These are shared as switch inputs 1 and 2 (Sw_1, Sw_2). The values of the analog inputs are automatically placed in VCL variables Analog1_Input and Analog2_Input every 1 millisecond. Scaling is 0–10V = 0–1023.

```
User2 = Analog2_Input
```

will fill the User2 RAM variable with the value of the voltage at pin 8.

The filtered values of the analog inputs are also available and are automatically placed in VCL variables Analog1_Filtered and Analog2_Filtered. Scaling is 0–10V = 0–1023. The default filter value is 328 (10 Hz) and can be changed in VCL by changing the Analog1_Filter and Analog2_Filter values. Scaling is 0–999 Hz = 0–32767.

Analog Output

The 1234E/36E/38E and 1234SE/36SE/38SE controllers have one analog output (pin 30); the 1232E/SE has no analog output. This output is a special driver output. The switching stage is filtered to provide a smooth average voltage, instead of the actual PWM waveform seen on Drivers 1–5. However, AnalogOut uses the same VCL functions Put_PWM() and Automate_PWM() used by these other drivers. The scaling is 0–10 V = 0–32767.

```
Put_PWM(PWM6,6553)
```

will generate 2.0 volts at the analog output. VCL can monitor this output using the variable Analog_Output.

INTERFACING THE THROTTLE AND BRAKE COMMANDS

VCL can interface and modify the throttle and brake signals at several points, from the potentiometer to the final motor controller command. VCL can be used to create a completely unique command, adjust parameters to provide MultiMode, or modify the throttle command based on steering angle, height, etc.

The throttle and brake signal chains within the controller are sophisticated and flexible. Before applying VCL to modify these chains, it is important to fully understand the ramifications of implementing changes. The motor and brake command signal chains are illustrated in Figure 15 and discussed below.

Throttle Processing

The top section of Figure 15 shows the throttle processing. The throttle signal chain flows left to right starting with the throttle pot (wiper). The voltage on the throttle wiper input (pin 16) is processed by the controller and has the VCL variable name *Throttle_Pot_Raw*. This variable is displayed as **Throttle Pot** (voltage) in the Monitor » Inputs menu of the 1313/1314 programmer. This throttle signal is then modified by the Throttle Type Processing and Throttle Mapping blocks.

The Throttle Type Processing block combines the Throttle_Type parameter and the throttle potentiometer input (Throttle_Pot_Raw) to create a 16-bit variable containing the magnitude of the raw command. This raw command passes to the Throttle Mapping block, which re-shapes the throttle signal magnitude and direction based on the various Throttle Menu parameters and the direction inputs.

Quick Links:
Figure 15 p.105
Throttle_Type parameter p.46
Throttle menu p.46
Pump parameter menu
  Speed Mode = 0 p.31
  Speed Mode = 1 p.32–39
Monitor Inputs p.70

Following the Throttle Mapping block are two switches whose purpose is to give the throttle signal a small value (1 for the forward switch, and –1 for the reverse switch) to indicate that a direction switch is On—but only if the throttle signal output from the Throttle Mapping block = 0.

The signal then passes through a selector switch. If the Throttle_Type parameter is set to 5 the Throttle Mapping block output signal is ignored and the command comes from the VCL variable VCL_Throttle. The VCL program manipulates the VCL_Throttle variable to get a throttle command. When the Throttle Type is set to 1–4, the variable VCL_Throttle does nothing, and the Throttle Mapping block output signal passes through.

After the "Throttle Type = 5" switch, the throttle signal is modified by the multiplying and summing nodes. These nodes can be adjusted by VCL through the variables Throttle_Multiplier and Throttle_Offset. This is the basic input point for creating functions like MultiMode, dual drive algorithms, and height vs. speed control. Note that the throttle multiplier has a built-in "divide by 128." This allows the VCL to either multiply (Throttle_Multiplier > 128) or divide (Throttle_Multiplier <128) the nominal throttle value. Typically the default multiplier is set to 128, thus having no net effect. Both Throttle_Multiplier and Throttle_Offset can be positive or negative.

The throttle signal next passes through a limiter that is active only if a pump motor is being operated (Pump Enable = On, and optionally if Regen Lower Enable = On, the pump motor can operate in reverse). This limiter acts to constrain the pump's throttle signal to 100% (positive for forward motion, or negative when Regen_Lower_Enable is On), which is appropriate for controlling a hydraulic pump motor in speed mode.

The output of the multiplying, summing and (pump) limiter nodes is the VCL variable called Mapped_Throttle, which is displayed as Mapped Throttle (percent) in the Monitor » Inputs menu of the 1313 handheld or 1314 PC programmers. A VCL program can control this throttle signal by changing the three variables VCL_Throttle (only if Throttle Type = 5), Throttle_Multiplier, and Throttle_Offset. The effect of these variables can be observed as in the 1313/1314's Mapped Throttle or the VCL Mapped_Throttle variables. Checking the value of Mapped Throttle (Mapped_Throttle) is a good way to see if your Throttle Menu parameters are set correctly.

Monitor menu
  Inputs » Interlock State p.70
  Controller » Main State p.74
Troubleshooting Chart p.132–139

Prior to passing to the final selector switch, the throttle signal passes through a selector which validates for forward pump operation in speed modes. It will set the pump throttle signal = 0% when, in either speed mode, Pump Enable = On and the Mapped_Throttle is < 0 (negative). This will prevent a pump operating in reverse when Regen Lower Enable = Off, or if the controller is in Torque Mode.

The throttle signal continues to a selector switch that will set the throttle signal = 0% if any of the following conditions are present: Interlock_State = Off, a fault has set throttle request = 0% (Fault action = ShutdownThrottle), or if Main_State ≠ 5 or 10, or an invalid throttle. An invalid throttle is when both the Forward and Reverse switches are On, for example.

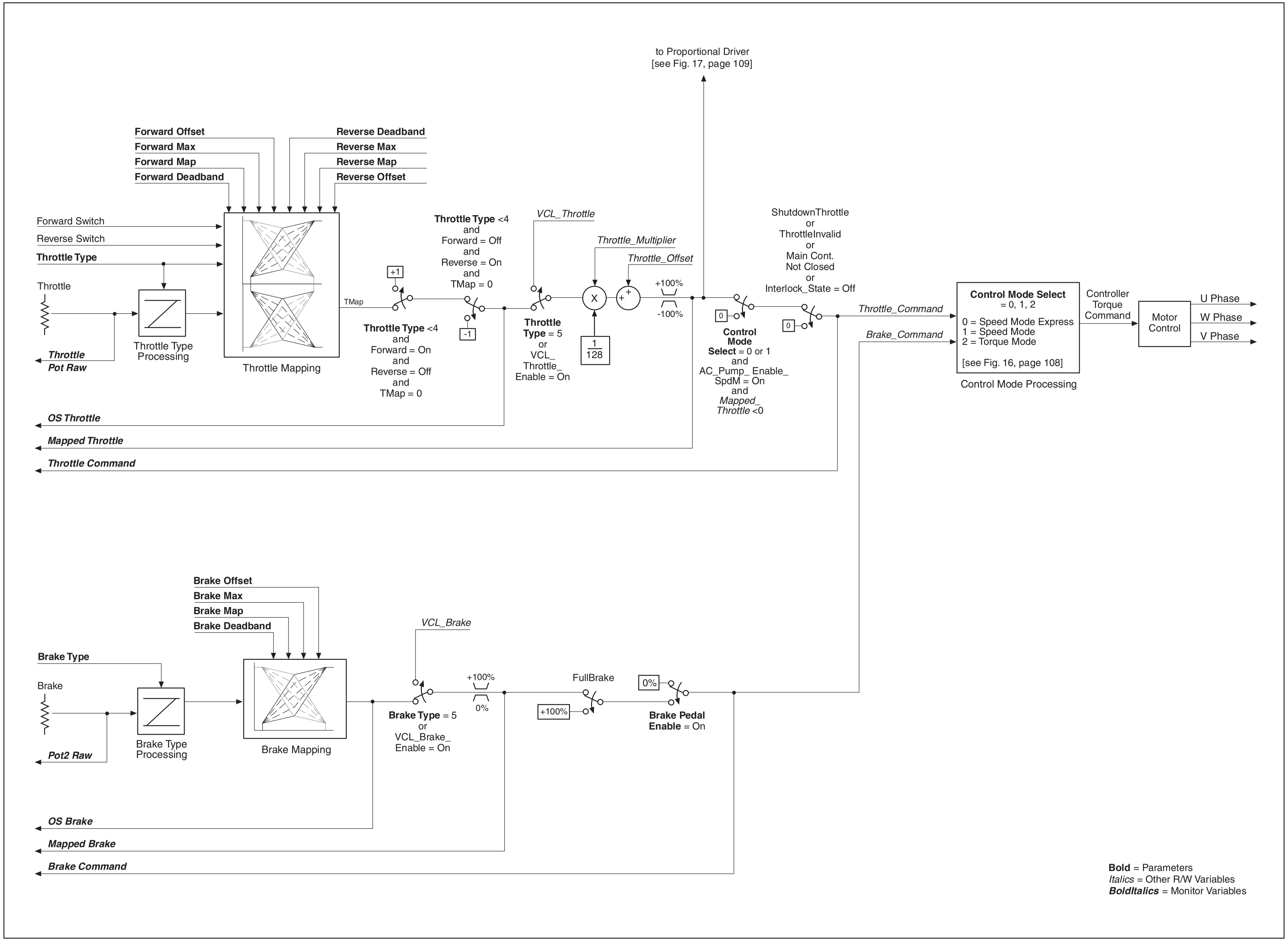


Figure 15

Motor command diagram.

After this final selector switch the throttle signal is the VCL variable called Throttle_Command, which is displayed as Throttle Command in the 1313/1314 Monitor » Inputs menu. Throttle_Command is the final value of the throttle signal chain that is input to the Control Mode Processing block; see Figure 16. Checking the value of Throttle Command using the 1313/1314 is a good way to see the final throttle signal.

If ABS (Throttle_Command) > 1 count, the motor controller will output signals to the motor to make it spin.

For investigating why a motor is not spinning, it is useful to use the 1313/1314 programmer to check the state of the throttle signal from beginning to end: using Throttle_Pot_Raw, Mapped_Throttle, and Throttle_Command. Once these values are known, the Motor Command Diagram (Figure 15) can be used to find how that signal progressed from input to final value.

The following throttle processing variables are accessible by VCL:

VCL Variable ***CAN Object Index***	**Access**	**Decription**
Throttle_Pot_Raw `0x3215 0x00`	Read Only	Voltage measurement at pin 16, scaled for the proper wiring.
OS_Throttle `0x3518 0x00`	Read Only	Throttle pot value after mapping, to be used in VCL when VCL Throttle Enable = On and Throttle Type = 1 – 4. Scale: 0 – 100%, 0 – 32,767
Mapped_Throttle `0x3211 0x00`	Read Only	Throttle pot value after mapping.
VCL_Throttle `0x3218 0x00`	Read/Write	VCL-accessible throttle command.
Throttle_Multiplier `0x3213 0x00`	Read/Write	Multiplies or divides the throttle signal.
Throttle_Offset `0x3214 0x00`	Read/Write	Provides a ± offset to the throttle signal.
Throttle_Command `0x3216 0x00`	Read Only	Command resulting from throttle processing.

Brake Processing

Brake processing is optional as it can be turned Off by setting Brake_Pedal_Enable = Off. If turned On, brake processing can be done with or without VCL. When the controller is in Speed Mode, any non-zero brake command will then override the throttle signal and the motor controller will brake to a stop as determined by the Brake Current Limit and Brake Taper Speed parameters. When the controller is in Torque Mode, the brake command is multiplied by 2 and subtracted from the throttle command to produce the final command; thus a 50% brake command will cancel a 100% throttle command.

Quick Links:
Brake Menu
  Brake Pedal Enable p.48
Current Limits Menu
  Brake Current Limit p.43
Brake Taper Speed p.41
Monitor
  Inputs » Pot2 Raw p.70
Figure 15 p.105
Figure 16 p.108

The lower part of Figure 15 shows the brake signal processing section. The brake signal chain flows from left to right starting with the physical brake pot. The voltage on the brake wiper input (pin 17) is processed by the controller and has the VCL variable name Pot2_Raw which is displayed as Pot2 Raw in the programmer's Monitor » Inputs menu. This brake signal is then modified by the Brake Type Processing and Brake Mapping blocks.

The Brake Type Processing block uses the Brake_Type parameter and the brake potentiometer input (Pot2_Raw) to create a signed 16-bit variable. This brake signal then passes to the Brake Mapping block, which re-shapes the brake signal according to the various Brake Menu parameters.

The brake signal next passes through a selector switch. If the Brake_Type parameter is set to 5 (Brake Type = VCL input), the Brake Mapping block output signal is ignored and the command comes from the VCL variable VCL_Brake. The VCL program manipulates the VCL_Brake variable to get a brake command. Custom braking functions can be set up in this fashion; e.g., braking based on a switch position or an internal fault. The brake potentiometer can still be used, but must be set up using the Setup_Pot() function. When the Brake Type is set to 1–4, the variable VCL_Brake does nothing and the Brake Mapping block output signal passes through.

After the "Brake Type = 5" switch, the brake signal passes through a limiter which limits the brake signal to a range of 0–100% (0–32767). After the limiter the brake signal is a VCL variable called Mapped_Brake, which is displayed as Mapped Brake in the Monitor » Inputs menu. Checking the value of Mapped_Brake is a good way to see if your Brake Menu parameters are set correctly. A VCL program can control the brake by changing the variable VCL_Brake (only if Brake Type = 5).

Quick Links:
Brake Menu
  Brake Pedal Enable p.48
Monitor Inputs
  Brake Command p.70
Figure 15 p.105
Figure 16 p.108

The brake signal then goes through a selector which will change it to 100% if the fault-action FullBrake is active. (see Troubleshooting Chart).

The brake signal then goes through a third selector switch that will set the brake signal = 0% if the Brake Pedal Enable parameter is set Off. If set On, then the brake signal will pass through to the Control Mode Processing block. The brake signal after this third selector switch is the VCL variable called Brake_Command and Brake Command in the Monitor » Inputs menu.

Brake_Command is the final value of the brake signal chain that is input to the Control Mode Processing block; see Figure 16. Checking the value of Brake_Command using the 1313 is a good way to see the final brake signal. Note: If Brake_Command is non-zero in Speed Mode Express or Speed Mode, the Throttle_Command will be set to 0% (see Fig. 16).

The following brake processing variables are accessible by VCL:

VCL Variable *CAN Object Index*	**Access**	**Decription**
Pot2_Raw `0x3217  0x00`	Read Only	Voltage measurement at pin 17.
OS_Brake `0x3519  0x00`	Read Only	Brake pot value after mapping, to be used in VCL when VCL Brake Enable = On and Brake Type = 1–3.
VCL_Brake `0x3219  0x00`	Read/Write	VCL-accessible brake command.
Mapped_Brake `0x3212  0x00`	Read Only	Brake pot value after mapping.
Brake_Command `0x321A  0x00`	Read Only	Command resulting from brake processing.

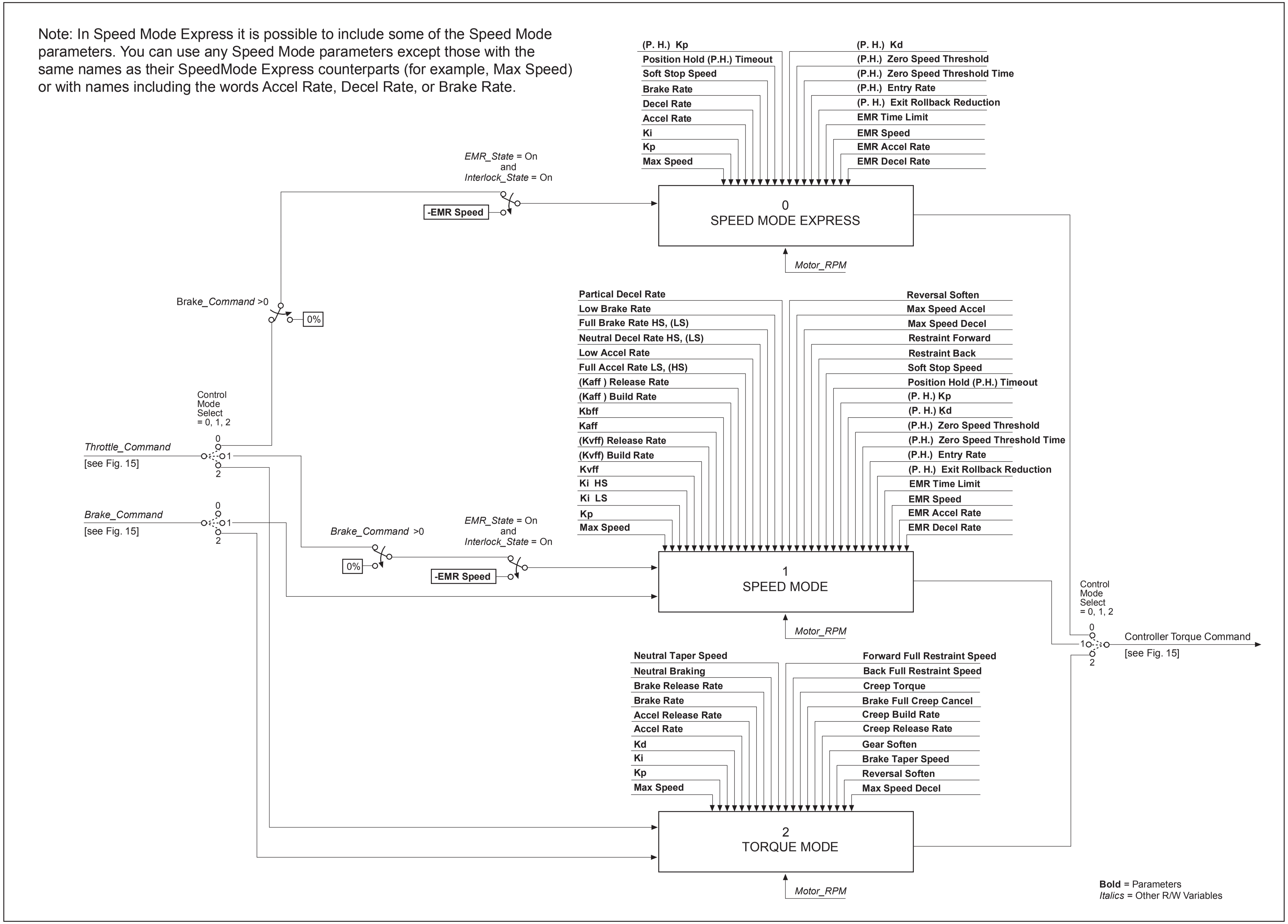
Control Mode and Motor Control Processing

Quick Links (for Control Mode and Motor Control Processing):
Figure 15 p.105
Figure 16 p.108
Motor Technology p.55
Motor Type p.57
Automated Characterization
  AC Induction motors p.85
  SPM w/Sin/Cos sensor p.91

Figure 16 begins with the Throttle_Command and Brake_Command inputs and routes the signals according to the selected control mode. For the speed modes, a switch will zero the Throttle_Command if the Brake_Command is any value but 0%. The signal chains are then directed to Speed Mode Express, Speed Mode, or Torque Mode based on Control Mode Select. Note that in Torque Mode there is no emergency reverse.

The control mode function uses algorithms to convert the incoming throttle and brake signals, the motor rpm, and associated parameter settings into a Controller Torque Command.

Based upon the control mode selected, the desired Controller Torque Command is calculated, which is passed to the Motor Control block (see Figure 15). The Motor Control block uses its mathematical model of the specific motor & technology to generate the high efficiency three-phase outputs that drive the AC motor via the cables connected to the U, V, and W terminals. For AC Induction motors, 323 motor characterizations are available using the Motor Type parameter, or a motor can be characterized (Motor Type 0) following the procedures in Chapter 8a. For application using an SPM motor and a Sin/Cos sensor, follow the automated characterization procedure in Chapter 8b. Always select the matching motor technology for the motor utilized.



Note: In Speed Mode Express it is possible to include some of the Speed Mode parameters. You can use any Speed Mode parameters except those with the same names as their SpeedMode Express counterparts (for example, Max Speed) or with names including the words Accel Rate, Decel Rate, or Brake Rate.

Figure 16
Control Mode processing.

INTERFACING THE PROPORTIONAL CURRENT DRIVER

VCL code can directly interface the proportional current driver (PD), as shown in Figure 17. VCL can change the working parameters of the PD and can provide the command.

Quick Links (for PD text):
Figure 17 p.109
Figure 3, PD Wiring p.12
Proportional Driver
parameters p.53
Monitor
PD Input p.71
PD PWM p.72
PD Current p.72

Depending on how the PD system is to be used, certain parameters need to be set; they can be set via the 1313/1314 programmer or via VCL.

1. **PD_Enable** must be set On for current control, otherwise the PD_Output will be controlled by the VCL function Put_PWM(PWM5,xxxx), which is voltage control.
2. **Hyd_Lower_Enable** must be set On to use the throttle input to control lowering in a hydraulic lift/lower system.
3. **Hyd_Lower_Enable** must be set Off to allow using a VCL variable (VCL_PD_Throttle) as the PD command.

Once the PD parameters are set, the PD_Throttle variable will be mapped between PD_Min_Current and PD_Max_Current and sent to the dither function. Note that Mapped_Throttle is inverted; lowering its value (making it more negative) increases the PD_Throttle value.

The Dither function adds and subtracts from the current command to the PD based on PD_Dither_Percent, at a rate set by PD_Dither_Period.

The dithered current command is compared to the present PD_Current and the error is fed into a PI controller. The feedback gains are set by the parameters PD Kp (proportional gain) and PD Ki (integral gain). The final output is the VCL variable PD_Output, which is displayed in the 1313/1314 programmer's Monitor » Outputs menu as PD PWM.

The following PD processing variables are accessible by VCL:

VCL Variable *CAN Object Index*	**Access**	**Decription**
Mapped_Throttle `0x3211   0x00`	Read Only	Command from throttle section.
VCL_PD_Throttle `0x320E   0x00`	Read/Write	VCL-accessible PD command.
PD_Throttle `0x3210   0x00`	Read Only	Resultant command to the PD.
PD_Current `0x321C   0x00`	Read Only	Average current flowing in the PD.
PD_Output `0x321E   0x00`	Read Only	Resultant PWM at PD output.

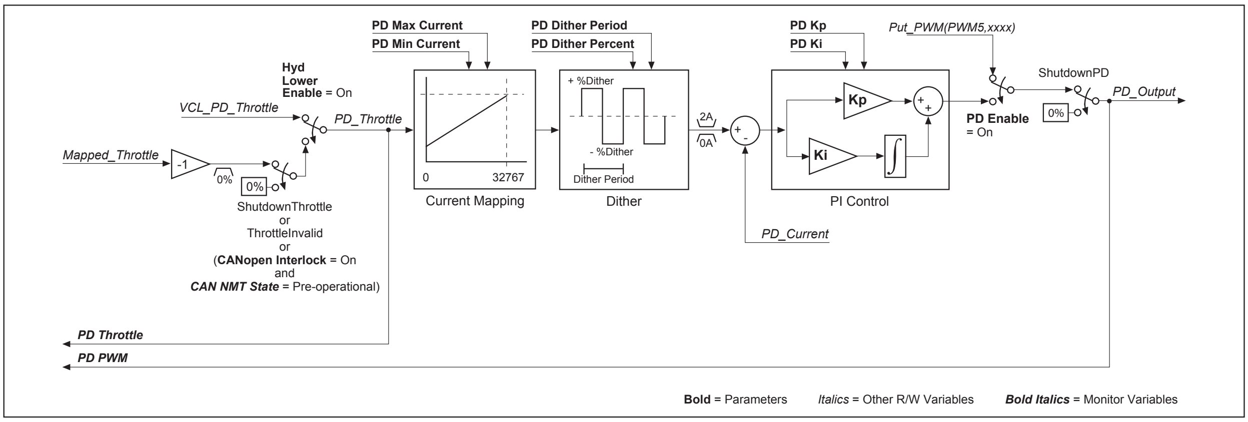


Figure 17
Proportional driver processing.

USING THE FAULT HANDLER IN VCL

The controller's operating system detects various faults and takes appropri-ate fault actions to protect the controller. These faults have fault codes that are flashed on the controller status LEDs. The fault text is displayed in the System Faults and Fault History menus of the 1313 handheld and 1314 PC programmers. These operating system faults are covered in more detail in Chapter 10's Troubleshooting Chart.

Additionally, the operating system makes the status of the operating system faults available for use in VCL programs in the form of nine variables called Status1, Status2, Status3, Status4, Status5, Status6, Status7, Status8, and Status9. Each of these 16-bit variables contains the status of 8 faults in the lower byte (the upper byte is always set to 0). These Status1–9 variables are read only (RO) and can be used in a VCL program to trigger additional fault actions such as sending fault text messages to a display or blinking a dashboard LED.

Listed below are the the bit locations of each of the operating system faults in the Status 1–9 variables, applicable to the default 1232E/SE - 1238E/SE controllers:

```
Status1

      Bit0 = Main Contactor Welded (Code 38)
      Bit1 = Main Contactor Did Not Close (Code 39)
      Bit2 = Pot Low OverCurrent (Code 45)
      Bit3 = Throttle Wiper Low (Code 42)
      Bit4 = Throttle Wiper High (Code 41)
      Bit5 = Pot2 Wiper Low (Code 44)
      Bit6 = Pot2 Wiper High (Code 43)
      Bit7 = EEPROM Failure (Code 46)

Status2

      Bit0 = HPD/Sequencing Fault (Code 47)
      Bit1 = Severe B+ Undervoltage (Code 17)
      Bit2 = Severe B+ Overvoltage (Code 18)
      Bit3 = B+ Undervoltage Cutback (Code 23)
      Bit4 = B+ Overvoltage Cutback (Code 24)
      Bit5 = Sin/Cos Sensor Fault (Code 36)
      Bit6 = Controller Overtemp Cutback (Code 22)
      Bit7 = Controller Severe Undertemp (Code 15)

Status3

      Bit0 = Controller Severe Overtemp (Code 16)
      Bit1 = Coil1 Driver Open/Short (Code 31)
      Bit2 = Coil2 Driver Open/Short (Code 32)
      Bit3 = Coil3 Driver Open/Short (Code 33)
      Bit4 = Coil4 Driver Open/Short (Code 34)
      Bit5 = PD Open/Short (Code 35)
      Bit6 = Main Open/Short (Code 31)
      Bit7 = EMBrake Open/Short (Code 32)
Status4

      Bit0 = Precharge Failed (Code 14)
      Bit1 = Digital Out 6 Open/Short (Code 26)
      Bit2 = Digital Out 7 Open/Short (Code 27)
      Bit3 = Controller Overcurrent (Code 12)
      Bit4 = Current Sensor Fault (Code 13)
      Bit5 = Motor Temp Hot Cutback (Code 28)
      Bit6 = Parameter Change Fault (Code 49)
      Bit7 = Motor Open (Code 37)
```

```
Status5

      Bit0 = External Supply Out of Range (Code 69)
      Bit1 = Motor Temp Sensor Fault (Code 29)
      Bit2 = VCL Run Time Error (Code 68)
      Bit3 = +5V Supply Failure (Code 25)
      Bit4 = OS General (Code 71)
      Bit5 = PDO Timeout (Code 72)
      Bit6 = Encoder Fault (Code 36)
      Bit7 = Stall Detected (Code 73)

Status6

      Bit0 = Bad Calibrations (Code 82)
      Bit1 = [Not Used]
      Bit2 = Emer Rev HPD (Code 47)
      Bit3 = [Not Used]
      Bit4 = Motor Type Fault (Code 89)
      Bit5 = Supervisor Fault (Code 77)
      Bit6 = Motor Characterization Fault (Code 87)
      Bit7 = [Not Used]

Status7

      Bit0 = [Not Used]
      Bit1 = VCL/OS Mismatch (Code 91)
      Bit2 = EM Brake Failed to Set (Code 92)
      Bit3 = Encoder LOS (Limited Operating Strategy) (Code 93)
      Bit4 = [Not Used]
      Bit5 = Dual Severe Fault (Code 75)
      Bit6 = Fault On Other Traction Controller (Code 74)
      Bit7 = Illegal Model Number (Code 98)

Status8

      Bit0 = [Not Used]
      Bit1 = [Not Used]
      Bit2 = [Not Used]
      Bit3 = Parameter Mismatch (Code 99)
      Bit4 = Severe KSI Undervoltage (Code 17)
      Bit5 = Severe KSI Overvoltage (Code 18)
      Bit6 = Insulation Resistance Low (Code 76)
      Bit7 = Encoder Pulse Count Fault (Code 88)

Status9

      Bit0 = Supervisor Incompatible (Code 78)
      Bit1 = [Not Used]
      Bit2 = [Not Used]
      Bit3 = [Not Used]
      Bit4 = [Not Used]
      Bit5 = [Not Used]
      Bit6 = Driver Supply (Code 83)
      Bit7 = [Not Used]
```

CANbus Emergency Messages

The Status1–9 faults form CAN emergency message using little-endian byte ordering, where: Byte1&2 is the Error Category, Byte3 is the error register which is "set" (01) if there is an active fault, and Bytes 4–8 map into the Status 1–9 faults as per the error category.

```
Error category = 0x1000 (for Status1 - Status5)
       Byte4 = Status1
       Byte5 = Status2
       Byte6 = Status3
       Byte7 = Status4
       Byte8 = Status5
Error category = 0x1001 (for Status6 - Status 10)
       Byte4 = Status6
       Byte5 = Status7
       Byte6 = Status8
       Byte7 = Status9
       Byte8 = Status … n/a (Status 10 is not utilized)
Example
CANbus error 00 10 01 00 00 00 08 00 equates to Status4, Bit3, Controller
Overcurrent (Code 12)
```

The OEM-defined user faults, described next, are also accessible in a CANbus emergency message.

```
Error category = 0x6200 (for UserFault1 and UserFault2, OEM Defined, implemented
in VCL)
       Byte4 = UserFault1
       Byte5 = UserFault2
       Byte6 = Not applicable
       Byte7 = Not applicable
       Byte8 = Not applicable
Example
CANbus error 00 62 01 02 00 00 00 equates to VCLfault1, Bit 1 (Code 52)
```

OEM-defined User Faults

The operating system provides the capability to create OEM-defined custom faults using VCL. Just as with system faults, the VCL fault codes are flashed on the controller Status LEDs and fault text is displayed on the System Faults and Fault History menus of the 1313/1314 programmer. Optionally, the VCL can assign fault actions to occur automatically when the associated fault is set. Sixteen VCL faults are available, stored in the VCL variables UserFault1 and UserFault2. The UserFault1,2 variables are Read/Write (R/W) and the 16 faults are mapped & stored in the lower byte of each variable as shown below:

```
UserFault1
        Bit0 = VCLfault1 (Code 51)
        Bit1 = VCLfault2 (Code 52)
        Bit2 = VCLfault3 (Code 53)
        Bit3 = VCLfault4 (Code 54)
        Bit4 = VCLfault5 (Code 55)
        Bit5 = VCLfault6 (Code 56)
        Bit6 = VCLfault7 (Code 57)
        Bit7 = VCLfault8 (Code 58)

UserFault2
        Bit0 = VCLfault9 (Code 59)
        Bit1 = VCLfault10 (Code 61)
        Bit2 = VCLfault11 (Code 62)
        Bit3 = VCLfault12 (Code 63)
        Bit4 = VCLfault13 (Code 64)
        Bit5 = VCLfault14 (Code 65)
        Bit6 = VCLfault15 (Code 66)
        Bit7 = VCLfault16 (Code 67)
```

The “Code” numbers result in the flashing of the controller status LEDs that help identify the fault without use of a 1313/1314 programmer. Setting the fault in VCL is done by setting the associated fault bit in the UserFault1 and 2 variables. Clearing the fault must also be handled by VCL and is done by clearing the associated fault bit. For example:

```
if (BDI-Percentage < 10)
{
UserFault1.2 = ON ;        Set VCL Fault bit
}
else
{
UserFault1.2 = OFF ;       Clear VCL Fault bit
}
```

This VCL will check to see if the Battery Discharge Indicator is less than 10%. If it is, UserFault1 Bit1 (Code 52) is set. If the BDI is not less than 10%, the fault is cleared. Using just the VCL above in a program will only result in the flashing of a code 52 on controller status LEDs and no fault actions will result nor will the 1313/1314 programmer display any text about the fault.

To add automatic fault actions to the VCL faults, the VCL programmer must define the desired fault actions by using the sixteen VCL variables: User_Fault_Action_01 through User_Fault_Action_16. Each of the UserFault bits has a corre-sponding User_Fault_Action_xx variable (where “xx” is the number of the VCL fault bit). When a VCL fault bit is set, the actions defined in the corresponding User_Fault_Action_xx variable will be automatically executed by the operating system. For any user fault, single or multiple actions can be specified. The available fault actions in the User_Fault_Actions_xx variables are listed below:

Variable	Fault Action
Bit0 = ShutdownMotor	Disable the motor.
Bit1 = ShutdownMainContactor	Shut down the main contactor (only if Main Enable = On)
Bit2 = ShutdownEMBrake	Shut down the EM brake (only if EM Brake Disable Upon Fault = On).
Bit3 = ShutdownThrottle	Set the Throttle_Command = 0%.
Bit4 = ShutdownInterlock	Set the Interlock_State = Off.
Bit5 = ShutdownDriverl	Shut down Driver1.
Bit6 = ShutdownDriver2	Shut down Driver2.
Bit7 = ShutdownDriver3	Shut down Driver3.
Bit8 = ShutdownDriver4	Shut down Driver4.
Bit9 = ShutdownPD	Shut down Proportional Driver
Bit10 = FullBrake	Set the Brake_Command = 100%.
Bit11 = [reserved]	N/A
Bit12 = TrimDisable	Disable Dual Drive trim calculation.
Bit13 = SevereDual	For Dual Drive system, one controller has a severe fault but the main contactor must stay closed so the other controller can continue to operate.
Bit14 = ShutdownSteer	Steer angle = 0°.
Bit15 = LOSDual	For Dual Drive system, set the max speed to Dual_LOS_Max_Speed parameter for operation in Limited Operating Strategy.

The User_Fault_Action_xx variables should be set up at the beginning of a VCL program (before the main loop) as these fault actions should be defined only once in a program. Here is another example:

```
User_Fault_Action_02 = 24 ;Set fault action to ShutdownInterlock
;and ShutdownThrottle
MainLoop:
if (BDI_Percentage < 10)
{
UserFault1.2 = ON ;        Set User Fault bit
Put_Spy_Text(“BDI Low”) ;  Send message to Model 840 display
}
else
{
UserFault1.2 = OFF ;       Clear User Fault bit
}
goto MainLoop
```

This time when UserFault1.2 is set, the operating system will ShutdownInterlock and ShutdownThrottle (which will result in a Throttle_Command = 0%) in ad-dition to flashing the code 52 on the controller status LEDs. An additional VCL line was added (Put_Spy_Text ("BDI Low")) to show how additional actions beyond those provided in the User_Fault_Action_xx can be programmed using VCL. In this example the Put_Spy_Text("BDI Low") will result in the message "BDI Low" appearing on the model 840 display (presumably as a message to the vehicle operator). This example will still not result in any display on the 1313/1314 programmer System Faults and Fault History menus.

To add the fault text on the System Faults and Fault History menus it is necessary to create a Fault Definition. Creating 1313/1314 fault definitions is a subject that is covered in detail in the VCL Programmer's Guide (Section 5, Support for the 1313/1314 Handheld Programmer). Here is an example of a fault definition:

```
User_Fault_Action_02 = 24 ;      Set fault action to ShutdownInterlock
                                 ;and ShutdownThrottle
MainLoop:
if (BDI_Percentage < 10)
{
UserFault1.2 = ON                ;Set User fault bit
Put_Spy_Text("BDI Low")          ;Send message to Model 840 display
}
else
{
UserFault1.2 = OFF               ;Clear User fault bit
}
goto MainLoop

; PARAMETER_ENTRY   "BDI Low Fault"
; TYPE              FAULTS
; WIDTH             8BIT
; ALT_ADDRESS       Hist_UserFault1
; ADDRESS           UserFault1
; BITSELECT         1
; BITACTIVELOW      NO
; END
```

This example will result in the exact same actions as the last example, except now the fault will be displayed in the programmer's System Faults menu (only while the fault is set) and this fault will be logged into the Fault History menu after being set. The text displayed in either of these menus will be the text defined in the fault definition (in this example "BDI Low Fault" will be displayed). The variable Hist_UserFault1 is listed as an ALT_ADDRESS. This line controls whether the fault gets logged into fault history (and thus appears in the programmer's Fault History menu). The two variables that can be used in the fault definitions for ALT_ADDRESS are Hist_UserFault1 and Hist_UserFault2; these should be used in the fault definitions with the corresponding UserFault1 and UserFault2 variables. If you wish to use VCL to clear fault history, use the VCL function Clear_Diaghist(). Also note that this example fault definition was for bit 1 of UserFault1. The VCL example set and cleared this bit by using the UserFault1.2 notation (".2" being the mask that defines bit 1).

CAN Indexes for the User Fault Variables

The CAN indexes for the various OEM-defined VCL user fault variables are shown below.

```
0x3238 0x00 UserFault1
0x389A 0x00 UserFault1_History
0x3231 0x00 Hist_UserFault1
0x3239 0x00 UserFault2
0x389B 0x00 UserFault2_History
0x3232 0x00 Hist_UserFault2
0x323B 0x00 User_Fault_Action_01
0x323C 0x00 User_Fault_Action_02
0x323D 0x00 User_Fault_Action_03
0x323E 0x00 User_Fault_Action_04
0x323F 0x00 User_Fault_Action_05
0x3240 0x00 User_Fault_Action_06
0x3241 0x00 User_Fault_Action_07
0x3242 0x00 User_Fault_Action_08
0x3243 0x00 User_Fault_Action_09
0x3244 0x00 User_Fault_Action_10
0x3245 0x00 User_Fault_Action_11
0x3246 0x00 User_Fault_Action_12
0x3247 0x00 User_Fault_Action_13
0x3248 0x00 User_Fault_Action_14
0x3249 0x00 User_Fault_Action_15
0x324A 0x00  User_Fault_Action_16
```

VCL FUNCTIONS SPECIFIC TO 1232E/SE, 1234E/SE, 1236E/SE, AND 1238E/SE CONTROLLERS

Function descriptions are provided here for the functions that are unique to these controllers. They are presented in the same format that is used in the VCL Common Functions Manual for the common functions.

ENABLE_PRECHARGE( )

This function is designed to precharge the capacitor bank before engaging a main contactor thereby preventing current surges and to protect controller internal components and main contactor tips. This function turns on the request for precharge of the capacitor bank from KSI.

When the precharge function is enabled, power will be supplied to the capacitor bank until the voltage is within the factory-set range of KSI, or the precharge time limit has expired, or the precharge resistor energy range has been exceeded. The current state of precharge is shown by the precharge variable (Precharge_State), which has the following values:

0 – Precharge has not yet been done.
1 – Precharge is in progress.
2 – Precharge has passed.
3 – Precharge has been aborted by the Disable_Precharge() function.
4 – Precharge has exceeded the precharge resistor energy limit.
5 – Precharge has exceeded the one-second time limit.

Syntax: **`Enable_Precharge()`**

Parameters: None.

Returns:

0 – Precharge not enabled.
1 – Precharge successfully enabled.

Error Codes: None.

Example: `Enable_Precharge()`

This will attempt to precharge the capacitor bank.

Note: Use this function only when the precharge is under VCL control.

DISABLE_PRECHARGE( )

This function is designed to abort the precharge function and clear any precharge fault. This function aborts the request for precharge of the capacitor bank from KSI. The resultant state of the precharge variable (Precharge_State) will be set to = 3 (for precharge aborted). The precharge states are:

0 – Precharge has not yet been done.
1 – Precharge is in progress.
2 – Precharge has passed.
3 – Precharge has been aborted by the Disable_Precharge() function.
4 – Precharge has exceeded the precharge resistor energy limit.
5 – Precharge has exceeded the one-second time limit.

Syntax: **`Disable_Precharge()`**

Parameters: None.

Returns:

0 – Precharge not enabled.
1 – Precharge successfully enabled.

Error Codes: None.

Example: `Disable_Precharge()`

This will attempt to abort the precharge of the capacitor bank and will clear any precharge fault.

SET_DIGOUT( )

This function turns on the selected digital output. The digital outputs are active low (On = driver on and pulled to ground, Off = open circuit at the pin).

Syntax: **`Set_Digout(DigOut_ID)`**

Parameters: DigOut_ID is the digital output identification.
DigOut6 = Digital Output 6 (pin 19).
DigOut7 = Digital Output 7 (pin 20).

Returns:

0 – Selected digital output not set.

1 – Selected digital output successfully set.

Error Codes: Bad_ID is returned when DigOut_ID is not in the range of DigOut6 to DigOut7.

Example: `Set_Digout(DigOut6)`

This example will set Digital Output 6 (pin 19) On (active low, pulled to ground).

CLEAR_DIGOUT( )

This function turns off the selected digital output. The digital outputs are active low (On = driver on and pulled to ground, Off = open circuit at the pin).

Syntax: **`Clear_Digout(DigOut_ID)`**

Parameters: DigOut_ID is the digital output identification.
DigOut6 = Digital Output 6 (pin 19).
DigOut7 = Digital Output 7 (pin 20).

Returns:

0 – Selected digital output not cleared.

1 – Selected digital output successfully cleared.

Error Codes: Bad_ID is returned when DigOut_ID is not in the range of DigOut6 to DigOut7.

Example: `Clear_Digout(DigOut6)`

This example will set Digital Output 6 (pin 19) Off (open circuit).

ENABLE_EMER_REV( )

This function is used to engage emergency reverse using VCL. The EMR Type parameter must be set to = 1 in order for the Enable_Emer_Rev() function to operate. If the system emergency reverse state is enabled (EMR_State bit variable = On), the emergency reverse function will operate according to the Emergency Reverse parameter settings; see page 65. To view the current emergency reverse state, see Monitor » Inputs: Emer Rev on the 1313/1314 programmer.

When the EMR_Type is set to = 1 and neither the Enable_Emer_Rev() nor the Disable_Emer_Rev() function has been called, the state for emergency reverse is Off (EMR_State bit variable = Off).

Syntax:	**`Enable_Emer_Rev()`**
Parameters:	None.
Returns:	
	0 – Emergency reverse not enabled.
	1 – Emergency reverse successfully enabled.
Error Codes:	None.
Example:	`Enable_Emer_Rev()`
	This will enable the emergency reverse function.

DISABLE_EMER_REV( )

This function is used to disengage emergency reverse using VCL. The EMR Type parameter must be set to = 1 in order for the Disable_Emer_Rev() function to operate. If the system emergency reverse state is disabled (EMR_State bit variable = Off), the emergency reverse function will stop operating and normal motor control function will resume (including an HPD/SRO check if the HPD/SRO Enable parameter is set to On). To view the current emergency reverse state, see Monitor » Inputs: Emer Rev on the 1313/1314 programmer.

When the EMR_Type is set to = 1 and neither the Enable_Emer_Rev() nor the Disable_Emer_Rev() function has been called, the state for emergency reverse is Off (EMR_State bit variable = Off).

Syntax:	**`Disable_Emer_Rev()`**
Parameters:	None.
Returns:	
	0 – Emergency reverse not disabled.
	1 – Emergency reverse successfully disabled.
Error Codes:	None.
Example:	`Disable_Emer_Rev()`
	This will disable the emergency reverse function.

SET_INTERLOCK( )

This function is used to engage the system interlock using VCL. The Interlock Type parameter (page 52) must be set to = 1 in order for the Set_Interlock() function to operate. If the system interlock is set (Interlock_State bit variable = On), the throttle input signal is allowed to pass along the throttle chain; see Figure 15. Additionally, if the main contactor is used (Main Enable parameter = On), setting the interlock will request the main closed state from the main contactor state machine. To view the current interlock state, see the Monitor » Inputs: Interlock. To view the current main contactor state, see Monitor » Controller: Main State.

When the Interlock_Type is set to = 1 and neither the Set_Interlock() nor the Clear_Interlock() function has been called, the state for the interlock is Off (Interlock_State bit variable = Off).

Syntax: **`Set_Interlock()`**

Parameters: None.

Returns:

0 – Interlock not set.

1 – Interlock successfully set.

Error Codes: None.

Example: `Set_Interlock()`

This will engage the system interlock.

CLEAR_INTERLOCK( )

This function is used to disengage the system interlock using VCL. The Interlock Type parameter must be set to = 1 in order for the Set_Interlock() function to operate. If the system interlock is cleared (Interlock_State bit variable = Off), the throttle input signal is not allowed to pass along the throttle chain; see Figure 15. Additionally, if the main contactor is used (Main Enable parameter = On), clearing the interlock will request the main open state from the main contactor state machine. To view the current interlock state, see Monitor » Inputs: Interlock. To view the current main contactor state, see Monitor » Controller: Main State.

When the Interlock_Type is set to = 1 and neither the Set_Interlock() nor Clear_Interlock() function has been called, the default state for the interlock is Off (Interlock_State bit variable = Off).

Syntax: **`Clear_Interlock()`**

Parameters: None.

Returns:

0 – Interlock not cleared.

1 – Interlock successfully cleared.

Error Codes: None.

Example: `Clear_Interlock()`

This will disengage the system interlock.

SETUP_POT( )

This function determines the type of electrical connection of the Throttle Wiper (J1-16) and Pot2 High (J1-27) potentiometers (pot inputs).

One wire pots are a 0 – 5 V input.
Two wire pots are rheostats.
Three wire pots use the pot-high and pot-low as their high and low references.

Syntax:	`Setup_Pot(Pot_ID, Type)`
Parameters:	
POT_ID	Pot (ID) Selector (THROTTLE_POT,or BRAKE_POT)
Type	Pot type (ONE_WIRE, TWO_WIRE, or THREE_WIRE)
Returns:	
0	Setup not successful
1	Setup successful
Errors	
BAD_ID	POT_ID out of Range
BAD_P_TYPE	Pot Type out of Range

GET_POT( )

This function returns the value of the selected pot; 0 – 32767 equating to 0 – 100% over the 0 – 5.00 V input range.

Syntax:	`Get_Pot(POT_ID)`
Parameters:	
POT_ID	Pot Selector (THROTTLE_POT,or BRAKE_POT)
Returns:	
0	Pot = 0 or error.
n	Pot value.
Errors	
BAD_ID	POT_ID out of Range

SETUP_POT_FAULTS( )

This function re-sets the upper and lower wiper fault voltages for the specified pot-input that will be used to activate a pot-wiper voltage fault. The valid range for the function parameters are 0 – 6.25 V (0 – 400 counts). If this function is not run, the default thresholds depend on the Throttle Type (or Brake Type) parameter setting; see table below. If the Throttle Type = 5 (or Brake Type = 5), the VCL function Setup_Pot will determine what fault thresholds are used.

Throttle Type	Low Fault Threshold	High Fault Threshold
1	0.1 V	5.5 V
2	NONE	5.5 V
3	0.1 V	5.5 V
4	0.1 V	5.5 V
5 (ONE_WIRE)	NONE	5.5 V
5 (TWO_WIRE)	0.1 V	5.5 V
5 (THREE_WIRE)	0.1 V	5.5 V

Syntax: **`Setup_Pot_Faults(Pot_ID, Low_Fault, High_Fault, Fault_Value)`**

Parameters: `Pot_ID` identifies the throttle whose fault limits are being set:

`Throttle_Pot`

`Brake_Pot`

`Low_Fault:` Specifies the lower threshold voltage limit.

Scaling: 1 V = 64 counts.

`High_Fault:` Specifies the upper threshold voltage limit.

Scaling: 1 V = 64 counts.

`Fault_Value:` The value that is used for the pot input when there is a fault (0–32767).

Scaling: ± 32767 = ± 100%.

Returns:

0 – Setup did not execute.

1 – Setup successful.

Error Codes: Bad_ID is returned when an incorrect pot ID is used.

Param_Range is returned when the voltage value is not within range.

Example: `Setup_Pot_Faults(THROTTLE_POT,19,320,4000)`

For the throttle pot, this will set the lower pot voltage to 0.3 V (19/64) and the upper pot voltage to 5.0 V (320/64). When there is a pot fault, the value of 4000 will be used. That is 4000/32767 of the full output, or roughly 12%.

START_PUMP( )

This function is used to turn on the pump lift contactor (pin 4). If the parameter Drivers » Driver3 » Contactor Enable = On (VCL HydraulicContactorEnable bit variable = On), the VCL function Start_Pump() will turn on the pump lift contactor (Driver 3).

When HydraulicContactorEnable = On and neither Start_Pump() nor Stop_ Pump() has been called, the pump lift contactor is Off.

Syntax:	**`Start_Pump()`**
Parameters:	None.
Returns:	
	0 – Pump start function not enabled.
	1 – Pump start function successfully enabled.
Error Codes:	None.
Example:	`Start_Pump()`
	This will turn on the pump lift contactor.

STOP_PUMP( )

This function is used to turn off the pump lift contactor (pin 4). If the parameter Drivers » Driver3 » Contactor Enable = On (VCL HydraulicContactorEnable bit variable = On), the VCL function Start_Pump() will turn off the pump lift contactor (Driver 3).

When HydraulicContactorEnable = On and neither Start_Pump() nor Stop_ Pump() has been called, the pump lift contactor is Off.

Syntax:	**`Stop_Pump()`**
Parameters:	None.
Returns:	
	0 – Pump stop function not enabled.
	1 – Pump stop function successfully enabled.
Error Codes:	None.
Example:	`Stop_Pump()`
	This will turn off the pump lift contactor.

AUTOMATE_FREQUENCY_OUTPUT( )

This function sets up the PD Driver (pin 2) PWM output to yield a frequency proportional to the input variable at an execution rate of 16 ms. This output can be used to drive an electronic speedometer or tachometer.

An additional VCL variable called Frequency_Output_Duty_Cycle works in conjunction with the Automate_Frequency_Output() function to modify the duty cycle of the output. The default value of Frequency_Output_Duty_Cycle is 50% (or

Syntax:	**`Automate_Frequency_Output()`**
Parameters:	
`@Source`	Index of source value to be the input.
`MinInput`	Holds the minimum value for the input.
`MaxInput`	Holds the maximum value for the input.
`MinOutput`	Holds the minimum value for the output in Hz.
`MaxOutput`	Holds the maximum value for the output in Hz. NOTE: The frequency range is 0–4000 Hz, with 4 Hz being the minimum active frequency, and 0–3 Hz = Off.
Returns:	0 – PWM not automated. 1 – PWM automated.
Error Codes:	Param_Range is returned when a parameter is out of range. PT_Range is returned when the Parameter Table Index is out of range.
Example:	To set up the PD Driver to output 500 Hz to 1500 Hz (at duty cycle = 25%) for motor speed in the range 100 rpm to 4000 rpm:

```
Frequency_Output_Duty_Cycle = 8192 ;set duty cycle = 25%
Automate_Frequency_Output(@ABS_Motor_Speed,100,4000,500,1500)
```

OVERRIDE_EM_BRAKE_PWM( )

This function is designed to override EM Brake. When this function is enabled, it resets the hill hold memory value.

Syntax:	`Override_EM_Brake_PWM(Kill_Hill_Hold)`
Parameters:	Kill_Hill_Hold
	0 – Retain hill hold memory.
	1 – Reset hill hold memory.
Returns:	
	0 – Failed to override EM brake.
	1 – Succeeded in overriding EM brake.
Error Codes:	None.

RESTORE_EM_BRAKE_PWM( )

This function returns control of the EM brake PWM to the EM brake state machine.

Syntax:	`Restore_EM_Brake_PWM()`
Parameters:	None
Returns:	
	0 – Failed
	1 – Success.
Error Codes:	None.

MAP_TWO_POINTS( )

This function interpolates values between two points, Y1 and Y2; based upon an X input parameter. Interpolating based on X1 and X2.

Typical Usage:

1. Calculate a value framed between two X-axis points projected across two Y points, where the functions' output is the value of the Y-axis intersection.
2. Extend the 7 pair limitation of the Setup_Map function by the use of multiple If, If Else statements on segments of an XY array.

Syntax:	**`Map_Two_Points(X,X1,X2,Y1,Y2)`**
Parameters:	
`X`	Input.
`X1`	Input point X1.
`X2`	Input point X2.
`Y1`	Output point Y1.
`Y2`	Output point Y2.
Returns:	
n	Mapped value.
Error Codes:	None.
Example:	Convert a controller value, such as Steer_Angle, to a voltage. The input (X) is the Steer_Angle variable, where X1-X2 is an angle between 0 and 90 Degrees. The output is the interpolated value across Y-axis points in Volts.

Enable the expansion of the Setup_Map(16) function beyond the seven (7) point-pair by the use of multiple If, If Else statements on segments of a two point XY array. For Example:

```
If(X < 1)
      {
      Y = Map_2_Points(X, X1, X2, Y1, Y2)
      }
Else If(0<= X <= 1)
      {
      Y = Map_two_Points(X, X1, X2, Y1, Y2)
      }
Else If(1< X <= 2)
      {
      Y = Map_Two_Points(X, X1, X2, Y1, Y2)
      }
Else If(2< X <= 3)
      {
      Y = Map_Two_Points(X, X1, X2, Y1, Y2)
      }
Etc.
```

BATTERY_COMPENSATE( )

This function is used to compensate a variable with battery voltage using the nominal battery setting.

Syntax:	`Battery_Compensate(Input)`
Parameters:	
Input	Variable to be compensated.
Returns:	
n	Output.
Error Codes:	None.

11 — DIAGNOSTICS AND TROUBLESHOOTING

These controllers detect a wide variety of faults or error conditions. Faults can be detected by the operating system or by the VCL code. This chapter describes the faults detected by the operating system

Faults detected by VCL code (faults 51–67 in Table 6) cannot be defined here as they will vary from application to application. Refer to the appropriate OEM documentation for information on these faults.

DIAGNOSTICS

Diagnostics information can be obtained in either of two ways: (1) by reading the display on a 1313 handheld or 1314 PC programmer or (2) by observing the fault codes issued by the Status LEDs. See Table 5 for a summary of LED display formats.

The 1313 /1314 programmer will display all faults that are currently set as well as a history of the faults that have been set since the history log was last cleared. The 1313/1314 displays the faults by name.

The pair of LEDs built into the controller (one red, one yellow) produce flash codes displaying all the currently set faults in a repeating cycle. Each code consists of two digits. The red LED flashes once to indicate that the first digit of the code will follow; the yellow LED then flashes the appropriate number of times for the first digit. The red LED flashes twice to indicate that the second digit of the code will follow; the yellow LED flashes the appropriate number of times for the second digit.

Example:

B+ Undervoltage Cutback (code 23).

In the Fault menu of the 1313/1314 programmer, the words B+ Undervoltage Cutback will be displayed; the real-time battery voltage is displayed in the Monitor menu (“Capacitor Voltage”).

The controller’s two LEDs will display this repeating pattern:

Red	Yellow	Red	Yellow
*	✲ ✲	* *	✲ ✲ ✲
(first digit)	(2)	(second digit)	(3)

The numerical codes used by the yellow LED are listed in the troubleshooting chart (Table 6), which also lists possible fault causes and describes the conditions that set and clear each fault.

Summary of LED Display Formats

The two LEDs have four different display modes, indicating the type of information they are providing.

Table 5 Types of LED Display

Display	Status
Neither LED illuminated	Controller is not powered on; or vehicle has dead battery; or severe damage.
Yellow LED flashing	Controller is operating normally.
Yellow and red LEDs both on solid	Controller is in Flash program mode.
Red LED on solid	Internal hardware fault detected by the Supervisor or Primary microprocessor. Missing or corrupt software. Interrupting a software download may cause corruption of the software. Cycle KSI to clear. Reload software or replace controller if necessary.
Red LED and yellow LED flashing alternately	Controller has detected a fault. 2-digit code flashed by yellow LED identifies the specific fault; one or two flashes by red LED indicate whether first or second code digit will follow.

TROUBLESHOOTING

The troubleshooting chart, Table 6, provides the following information on all the controller faults:

- fault code
- fault name as displayed on the programmer's LCD
- the effect of the fault
- possible causes of the fault
- fault set conditions
- fault clear conditions.

Whenever a fault is encountered and no wiring or vehicle fault can be found, shut off KSI and turn it back on to see if the fault clears. If it does not, shut off KSI and remove the 35-pin connector. Check the connector for corrosion or damage, clean it if necessary, and re-insert it.

The fault actions (effect of fault) in Table 6 use the same bit-structure as the User_Fault_Action_xx listed in the OEM-defined User Faults on page 113. The variable System_Action (available in WinVCL Monitor or TACT) returns the decimal number corresponding to the active fault action bit(s). The Dual Drive fault actions, Bits 12–15, are listed in the supplemental Dual Drive Operation manual.

System_Action Bit	Action
No defined System_Action	Effect of fault as noted in Table 6
Bit0 = ShutdownMotor	Disable the motor.
Bit1 = ShutdownMainContactor	Shut down the main contactor (only if Main Enable = On)
Bit2 = ShutdownEMBrake	Shut down the EM brake (only if EM Brake Disable Upon Fault = On).
Bit3 = ShutdownThrottle	Set the Throttle_Command = 0%.
Bit4 = ShutdownInterlock	Set the Interlock_State = Off.
Bit5 = ShutdownDriverl	Shut down Driver1.
Bit6 = ShutdownDriver2	Shut down Driver2.
Bit7 = ShutdownDriver3	Shut down Driver3.
Bit8 = ShutdownDriver4	Shut down Driver4.
Bit9 = ShutdownPD	Shut down Proportional Driver
Bit10 = FullBrake	Set the Brake_Command = 100%.
Bit11 = [reserved]	N/A (for 1232–1238E/SE, and 1239E controllers)
Bit12 = TrimDisable	Disable Dual Drive trim calculation.
Bit13 = SevereDual	For Dual Drive system, one controller has a severe fault but the main contactor must stay closed so the other controller can continue to operate.
Bit14 = ShutdownSteer	Steer angle = 0° (DD applicable).
Bit15 = LOSDual	For Dual Drive system, set the max speed to Dual_LOS_Max_Speed parameter for operation in Limited Operating Strategy.

Example:

```
HPD/Sequencing Fault, Flash Code 47.
Effect of fault = Shutdown Throttle.
System_Action = 8 (equates to Bit3 set: 0000 0000 0000 1000)
```

Table 6 TROUBLESHOOTING CHART

CODE	PROGRAMMER LCD DISPLAY *EFFECT OF FAULT*	POSSIBLE CAUSE	SET / CLEAR CONDITIONS
12	**Controller Overcurrent** *ShutdownMotor;* *ShutdownMainContactor;* *ShutdownEMBrake;* *ShutdownThrottle;* *FullBrake.*	1. External short of phase U,V, or W motor connections. 2. Motor parameters are mis-tuned. 3. Controller defective. 4. Speed encoder noise problems.	*Set:* Phase current exceeded the current measurement limit. *Clear:* Cycle KSI.
13	**Current Sensor Fault** *ShutdownMotor;* *ShutdownMainContactor;* *ShutdownEMBrake;* *ShutdownThrottle;* *FullBrake.*	1. Leakage to vehicle frame from phase U, V, or W (short in motor stator). 2. Controller defective.	*Set:* Controller current sensors have invalid offset reading. *Clear:* Cycle KSI.
14	**Precharge Failed** *ShutdownMotor;* *ShutdownMainContactor;* *ShutdownEMBrake;* *ShutdownThrottle;* *FullBrake.*	1. See Monitor menu » Battery: Capacitor Voltage. 2. External load on capacitor bank (B+ connection terminal) that prevents the capacitor bank from charging.	*Set:* The precharge failed to charge the capacitor bank. *Clear:* Cycle Interlock input or use VCL function *Enable_Precharge().*
15	**Controller Severe Undertemp** *ShutdownMotor;* *ShutdownMainContactor;* *ShutdownEMBrake;* *ShutdownThrottle;* *FullBrake.*	1. See Monitor menu » Controller: Temperature. 2. Controller is operating in an extreme environment.	*Set:* Heatsink temperature below -40°C. *Clear:* Bring heatsink temperature above -40°C, and cycle interlock or KSI.
16	**Controller Severe Overtemp** *ShutdownMotor;* *ShutdownMainContactor;* *ShutdownEMBrake;* *ShutdownThrottle;* *FullBrake.*	1. See Monitor menu » Controller: Temperature. 2. Controller is operating in an extreme environment. 3. Excessive load on vehicle. 4. Improper mounting of controller.	*Set:* Heatsink temperature above +95°C. *Clear:* Bring heatsink temperature below +95°C, and cycle interlock or KSI.
17	**Severe B+ Undervoltage** *No drive torque.*	1. Battery parameters are misadjusted. 2. Non-controller system drain on battery. 3. Battery resistance too high. 4. Battery disconnected while driving. 5. See Monitor menu » Battery: Capacitor Voltage. 6. Blown B+ fuse or main contactor did not close.	*Set:* Capacitor bank voltage dropped below the Severe Undervoltage limit (see page 25) with FET bridge enabled. *Clear:* Bring capacitor voltage above Severe Undervoltage limit.
17	**Severe KSI Undervoltage** *No action.*	1. See Monitor menu » Battery: Keyswitch Voltage. 2. Non-controller system drain on battery/ KSI circuit wiring. 3. KSI disconnected while driving. 4. Blown KSI fuse.	*Set:* When below Brownout Voltage for 2 seconds (see Table D-1). *Clear:* Bring KSI voltage above Brownout Voltage.
18	**Severe B+ Overvoltage** *ShutdownMotor;* *ShutdownMainContactor;* *ShutdownEMBrake;* *ShutdownThrottle;* *FullBrake.*	1. See Monitor menu » Battery: Capacitor Voltage. 2. Battery parameters are misadjusted. 3. Battery resistance too high for given regen current. 4. Battery disconnected while regen braking.	*Set:* Capacitor bank voltage exceeded the Severe Overvoltage limit (see page 25) with FET bridge enabled. *Clear:* Bring capacitor voltage below Severe Overvoltage limit, and then cycle KSI.

Table 6 TROUBLESHOOTING CHART cont'd

CODE	PROGRAMMER LCD DISPLAY *EFFECT OF FAULT*	POSSIBLE CAUSE	SET / CLEAR CONDITIONS
18	**Severe KSI Overvoltage** *ShutdownMotor;* *ShutdownMainContactor;* *ShutdownEMBrake;* *ShutdownThrottle;* *FullBrake.*	1. Incorrect (to high) battery-voltage applied to KSI (pin 1) 2. See Monitor menu » Battery: Keyswitch Voltage. Note: Prevents the Main Contactor closure if KSI is greater than the Severe Overvoltage limit.	*Set:* KSI voltage exceeded Severe Overvoltage limiit *Clear:* Bring KSI voltage below the Severe Overvoltage limit (see page 25, Severe Overvoltage)
22	**Controller Overtemp Cutback** *Reduced drive and brake torque.*	1. See Monitor menu » Controller: Temperature. 2. Controller is performance-limited at this temperature. 3. Controller is operating in an extreme environment. 4. Excessive load on vehicle. 5. Improper mounting of controller.	*Set:* Heatsink temperature exceeded 85°C. *Clear:* Bring heatsink temperature below 85°C.
23	**B+ Undervoltage Cutback** *Reduced drive torque.*	1. Normal operation. Fault indicates the batteries need recharging. Controller is performance limited at this voltage. 2. Battery parameters are misadjusted. 3. Non-controller system drain on battery. 4. Battery resistance too high. 5. Battery disconnected while driving. 6. See Monitor menu » Battery: Capacitor Voltage. 7. Blown B+ fuse or main contactor did not close.	*Set:* Capacitor bank voltage dropped below the Undervoltage limit (see page 25) with the FET bridge enabled. *Clear:* Bring capacitor voltage above the Undervoltage limit.
24	**B+ Overvoltage Cutback** *Reduced brake torque. Note: This fault is declared only when the controller is running in regen.*	1. Normal operation. Fault shows that regen braking currents elevated the battery voltage during regen braking. Controller is performance limited at this voltage. 2. Battery parameters are misadjusted. 3. Battery resistance too high for given regen current. 4. Battery disconnected while regen braking. 5. See Monitor menu » Battery: Capacitor Voltage.	*Set:* Capacitor bank voltage exceeded the Overvoltage limit (see page 25) with the FET bridge enabled. *Clear:* Bring capacitor voltage below the Overvoltage limit.
25	**+5V Supply Failure** *None, unless a fault action is programmed in VCL.*	1. External load impedance on the +5V supply (pin 26) is too low. 2. See Monitor menu » outputs: 5 Volts and Ext Supply Current.	*Set:* +5V supply (pin 26) outside the 5 V±10% range. *Clear:* Bring voltage within range.
26	**Digital Out 6 Open/Short** *Digital Output 6 driver will not turn on.*	1. External load impedance on Digital Output 6 driver (pin 19) is too low.	*Set:* Digital Output 6 (pin 19) current exceeded 1 Amp. *Clear:* Remedy the overcurrent cause and use the VCL function *Set_DigOut()* to turn the driver on again.
27	**Digital Out 7 Open/Short** *Digital Output 7 driver will not turn on.*	1. External load impedance on Digital Output 7 driver (pin 20) is too low.	*Set:* Digital Output 7 (pin 20) current exceeded 1 Amp. *Clear:* Remedy the overcurrent cause and use the VCL function *Set_DigOut()* to turn the driver on again.

Table 6 TROUBLESHOOTING CHART cont'd

CODE	PROGRAMMER LCD DISPLAY *EFFECT OF FAULT*	POSSIBLE CAUSE	SET / CLEAR CONDITIONS
28	**Motor Temp Hot Cutback** *Reduced drive torque.*	1. Motor temperature is at or above the programmed Temperature Hot setting, and the current is being cut back. 2. Motor Temperature Control Menu parameters are mis-tuned. 3. See Monitor menu » Motor: Temperature and » Inputs: Analog2. 4. If the application doesn't use a motor thermistor, Temp Compensation and Temp Cutback should be programmed Off.	*Set:* Motor temperature is at or above the Temperature Hot parameter setting. *Clear:* Bring the motor temperature within range.
29	**Motor Temp Sensor Fault** *MaxSpeed reduced (LOS, Limited Operating Strategy), and motor temperature cutback disabled.*	1. Motor thermistor is not connected properly. 2. If the application doesn't use a motor thermistor, Motor Temp Sensor Enable should be programmed Off. 3. See Monitor menu » Motor: Temperature and » Inputs: Analog2.	*Set:* Motor thermistor input (pin 8) is at the voltage rail (0 V or 10 V). *Clear:* Bring the motor thermistor input voltage within range.
31	**Coil1 Driver Open/Short** *ShutdownDriver1.*	1. Open or short on driver load. 2. Dirty connector pins. 3. Bad crimps or faulty wiring.	*Set:* Driver 1 (pin 6) is either open or shorted. This fault can be set only when Main Enable = Off. *Clear:* Correct open or short, and cycle driver.
31	**Main Open/Short** *ShutdownMotor;* *ShutdownMainContactor;* *ShutdownEMBrake;* *ShutdownThrottle;* *FullBrake.*	1. Open or short on driver load. 2. Dirty connector pins. 3. Bad crimps or faulty wiring.	*Set:* Main contactor driver (pin 6) is either open or shorted. This fault can be set only when Main Enable = On. *Clear:* Correct open or short, and cycle driver
32	**Coil2 Driver Open/Short** *ShutdownDriver2.*	1. Open or short on driver load. 2. Dirty connector pins. 3. Bad crimps or faulty wiring.	*Set:* Driver 2 (pin 5) is either open or shorted. This fault can be set only when EM Brake Type = 0. *Clear:* Correct open or short, and cycle driver.
32	**EMBrake Open/Short** *ShutdownEMBrake;* *ShutdownThrottle;* *FullBrake.*	1. Open or short on driver load. 2. Dirty connector pins. 3. Bad crimps or faulty wiring.	*Set:* Electromagnetic brake driver (pin 5) is either open or shorted. This fault can be set only when EM Brake Type >0. *Clear:* Correct open or short, and cycle driver.
33	**Coil3 Driver Open/Short** *ShutdownDriver3.*	1. Open or short on driver load. 2. Dirty connector pins. 3. Bad crimps or faulty wiring.	*Set:* Driver 3 (pin 4) is either open or shorted. *Clear:* Correct open or short, and cycle driver.
34	**Coil4 Driver Open/Short** *ShutdownDriver4.*	1. Open or short on driver load. 2. Dirty connector pins. 3. Bad crimps or faulty wiring.	*Set:* Driver 4 (pin 3) is either open or shorted. *Clear:* Correct open or short, and cycle driver.
35	**PD Open/Short** *ShutdownPD.*	1. Open or short on driver load. 2. Dirty connector pins. 3. Bad crimps or faulty wiring.	*Set:* Proportional driver (pin 2) is either open or shorted. *Clear:* Correct open or short, and cycle driver.
36	**Encoder Fault** *ShutdownEMBrake;* Motor disabled.	1. Motor encoder failure. 2. Bad crimps or faulty wiring. 3. See Monitor menu » Motor: Motor RPM.	*Set:* Motor encoder phase failure detected. *Clear:* Either cycle KSI, or if parameter LOS Upon Encoder Fault= On and Interlock has been cycled, then the Encoder Fault is cleared and Encoder LOS fault (code 93) is set, allowing limited motor control.
36	**Sin/Cos Sensor Fault** *ShutdownEMBrake;* Motor disabled.	1. Sin/Cos sensor failure. 2. Bad crimps or faulty wiring. 3. See Monitor menu » Motor: Motor RPM.	*Set:* Greater than Sin_Cos_Fault_Threshold % difference from expected value between two phases seen 5 times within one second. *Clear:* Cycle KSI, or VCL reset, or Entry into LOS mode if enabled, (or entry into an ACIM auto-characterization).

Table 6 TROUBLESHOOTING CHART cont'd

CODE	PROGRAMMER LCD DISPLAY *EFFECT OF FAULT*	POSSIBLE CAUSE	SET / CLEAR CONDITIONS
37	**Motor Open** *ShutdownMotor;* *ShutdownMainContactor;* *ShutdownEMBrake;* *ShutdownThrottle;* *FullBrake.*	1. Motor phase is open. 2. Bad crimps or faulty wiring.	*Set:* Motor phase U, V, or W detected open. *Clear:* Cycle KSI.
38	**Main Contactor Welded** *ShutdownMotor;* *ShutdownMainContactor;* *ShutdownEMBrake;* *ShutdownThrottle;* *FullBrake.*	1. Main contactor tips are welded closed. 2. Motor phase U or V is disconnected or open. 3. An alternate voltage path (such as an external precharge resistor) is providing a current to the capacitor bank (B+ connection terminal).	*Set:* Just prior to the main contactor closing, the capacitor bank voltage (B+ connection terminal) was loaded for a short time and the voltage did not discharge. *Clear:* Cycle KSI
39	**Main Contactor Did Not Close** *ShutdownMotor;* *ShutdownMainContactor;* *ShutdownEMBrake;* *ShutdownThrottle;* *FullBrake.*	1. Main contactor did not close. 2. Main contactor tips are oxidized, burned, or not making good contact.* 3. External load on capacitor bank (B+ connection terminal) that prevents capacitor bank from charging. 4. Blown B+ fuse.	*Set:* With the main contactor commanded closed, the capacitor bank voltage (B+ connection terminal) did not charge to B+. *Clear:* Cycle KSI. *New contactors may need to be cycled electrically & mechanically to remove any non-conductive material on the tips. Use reduced voltage (e.g., 12V) to prevent tip damage through excessive arcing.
41	**Throttle Wiper High** *ShutdownThrottle.*	1. See Monitor menu » Inputs: Throttle Pot. 2. Throttle pot wiper voltage too high.	*Set:* Throttle pot wiper (pin 16) voltage is higher than the high fault threshold (can be changed with the VCL function *Setup_Pot_Faults()*). *Clear:* Bring throttle pot wiper voltage below the fault threshold.
42	**Throttle Wiper Low** *ShutdownThrottle.*	1. See Monitor menu » Inputs: Throttle Pot. 2. Throttle pot wiper voltage too low.	*Set:* Throttle pot wiper (pin 16) voltage is lower than the low fault threshold (can be changed with the VCL function *Setup_Pot_Faults()*). *Clear:* Bring throttle pot wiper voltage above the fault threshold.
43	**Pot2 Wiper High** *FullBrake.*	1. See Monitor menu » Inputs: Pot2 Raw. 2. Pot2 wiper voltage too high.	*Set:* Pot2 wiper (pin 17) voltage is higher than the high fault threshold (can be changed with the VCL function *Setup_Pot_Faults()*). *Clear:* Bring Pot2 wiper voltage below the fault threshold.
44	**Pot2 Wiper Low** *FullBrake.*	1. See Monitor menu » Inputs: Pot2 Raw. 2. Pot2 wiper voltage too low.	*Set:* Pot2 wiper (pin 17) voltage is lower than the low fault threshold (can be changed with the VCL function *Setup_Pot_Faults()*). *Clear:* Bring Pot2 wiper voltage above the fault threshold.
45	**Pot Low OverCurrent** *ShutdownThrottle;* *FullBrake.*	1. See Monitor menu » Outputs: Pot Low. 2. Combined pot resistance connected to pot low is too low.	*Set:* Pot low (pin 18) current exceeds 10 mA. *Clear:* Clear pot low overcurrent condition and cycle KSI.
46	**EEPROM Failure** *ShutdownMotor;* *ShutdownMainContactor;* *ShutdownEMBrake;* *ShutdownThrottle;* *ShutdownInterlock;* *ShutdownDriver1;* *ShutdownDriver2;* *ShutdownDriver3;* *ShutdownDriver4;* *ShutdownPD;* *FullBrake.*	1. Failure to write to EEPROM memory. This can be caused by EEPROM memory writes initiated by VCL, by the CAN bus, by adjusting parameters with the programmer, or by loading new software into the controller.	*Set:* Controller operating system tried to write to EEPROM memory and failed. *Clear:* Download the correct software (OS) and matching parameter default settings into the controller and cycle KSI.

Table 6 TROUBLESHOOTING CHART cont'd

CODE	PROGRAMMER LCD DISPLAY *EFFECT OF FAULT*	POSSIBLE CAUSE	SET / CLEAR CONDITIONS
47	**HPD/Sequencing Fault** *ShutdownThrottle.*	1. KSI, interlock, direction, and throttle inputs applied in incorrect sequence. 2. Faulty wiring, crimps, or switches at KSI, interlock, direction, or throttle inputs. 3. See Monitor menu » Inputs.	*Set:* HPD (High Pedal Disable) or sequencing fault caused by incorrect sequence of KSI, interlock, direction, and throttle inputs. *Clear:* Reapply inputs in correct sequence.
47	**Emer Rev HPD** *ShutdownThrottle;* *ShutdownEMBrake.*	4. Emergency Reverse operation has concluded, but the throttle, forward and reverse inputs, and interlock have not been returned to neutral.	*Set:* At the conclusion of Emergency Reverse, the fault was set because various inputs were not returned to neutral. *Clear:* If EMR_Interlock = On, clear the interlock, throttle, and direction inputs. If EMR_Interlock = Off, clear the throttle and direction inputs.
49	**Parameter Change Fault** *ShutdownMotor;* *ShutdownMainContactor;* *ShutdownEMBrake;* *ShutdownThrottle;* *FullBrake.*	1. This is a safety fault caused by a change in certain parameter settings so that the vehicle will not operate until KSI is cycled. For example, if a user changes the Throttle Type this fault will appear and require cycling KSI before the vehicle can operate.	*Set:* Adjustment of a parameter setting that requires cycling of KSI. *Clear:* Cycle KSI.
51-67	**OEM Faults** *(See OEM documentation.)*	1. These faults can be defined by the OEM and are implemented in the application-specific VCL code. See OEM documentation.	*Set:* See OEM documentation. *Clear:* See OEM documentation.
68	**VCL Run Time Error** *ShutdownMotor;* *ShutdownMainContactor;* *ShutdownEMBrake;* *ShutdownThrottle;* *ShutdownInterlock;* *ShutdownDriver1;* *ShutdownDriver2;* *ShutdownDriver3;* *ShutdownDriver4;* *ShutdownPD;* *FullBrake.*	1. VCL code encountered a runtime VCL error. 2. See Monitor menu » Controller: VCL Error Module and VCL Error. This error can then be compared to the runtime VCL module ID and error code definitions found in the specific OS system information file.	*Set:* Runtime VCL code error condition. *Clear:* Edit VCL application software to fix this error condition; flash the new compiled software and matching parameter defaults; cycle KSI.
69	**External Supply Out of Range** *None, unless a fault action is programmed in VCL.*	1. External load on the 5V and 12V supplies draws either too much or too little current. 2. Fault Checking Menu parameters Ext Supply Max and Ext Supply Min are mis-tuned. 3. See Monitor menu » Outputs: Ext Supply Current.	*Set:* The external supply current (combined current used by the 5V supply [pin 26] and 12V supply [pin 25]) is either greater than the upper current threshold or lower than the lower current threshold. The two thresholds are defined by the External Supply Max and External Supply Min parameter settings (page 54). *Clear:* Bring the external supply current within range.
71	**OS General** *ShutdownMotor;* *ShutdownMainContactor;* *ShutdownEMBrake;* *ShutdownThrottle;* *ShutdownInterlock;* *ShutdownDriver1;* *ShutdownDriver2;* *ShutdownDriver3;* *ShutdownDriver4;* *ShutdownPD;* *FullBrake.*	1. Internal controller fault.	*Set:* Internal controller fault detected. *Clear:* Cycle KSI.
72	**PDO Timeout** *ShutdownThrottle;* CAN NMT State set to Pre-operational.	1. Time between CAN PDO messages received exceeded the PDO Timeout Period.	*Set:* Time between CAN PDO messages received exceeded the PDO Timeout Period. *Clear:* Cycle KSI or receive CAN NMT message.

Table 6 TROUBLESHOOTING CHART cont'd

CODE	PROGRAMMER LCD DISPLAY *EFFECT OF FAULT*	POSSIBLE CAUSE	SET / CLEAR CONDITIONS
73	**Stall Detected** *ShutdownEMBrake;* Motor disabled; Control Mode changed to LOS (Limited Operating Strategy).	1. Stalled motor. 2. Motor encoder failure. 3. Bad crimps or faulty wiring. 4. Problems with power supply for the motor encoder. 5. See Monitor menu » Motor: Motor RPM.	*Set:* No motor encoder movement detected. *Clear:* Either cycle KSI, or if parameter LOS Upon Encoder Fault = On and Interlock has been cycled, then the Stall Detected fault is cleared and Encoder LOS fault (code 93) is set, allowing limited motor control.
74	**Fault On Other Traction Controller**	1. Dual Drive fault: see Dual Drive manual.	
75	**Dual Severe Fault**	1. Dual Drive fault: see Dual Drive manual.	
77	**Supervisor Fault** *ShutdownMotor;* *ShutdownMainContactor;* *ShutdownEMBrake;* *ShutdownThrottle;* *ShutdownInterlock;* *ShutdownDriver1;* *ShutdownDriver2;* *ShutdownDriver3;* *ShutdownDriver4;* *ShutdownPD;* *FullBrake.*	1. The Supervisor has detected a mismatch in redundant readings. 2. Internal damage to Supervisor microprocessor. 3. Switch inputs allowed to be within upper and lower thresholds for over 100 milliseconds. (for recurring errors, check the switches for moisture).	*Set:* Mismatched redundant readings; damaged Supervisor; illegal switch inputs. *Clear:* Check for noise or voltage drift in all switch inputs; check connections; cycle KSI.
78	**Supervisor Incompatible** *ShutdownMotor;* *ShutdownMainContactor;* *ShutdownEMBrake;* *ShutdownThrottle;* *ShutdownInterlock;* *ShutdownDriver1;* *ShutdownDriver2;* *ShutdownDriver3;* *ShutdownDriver4;* *ShutdownPD;* *FullBrake.*	1. The main OS is not compatible with the Supervisor OS.	*Set:* Incompatible software. *Clear:* Load properly matched OS code or update the Supervisor code; cycle KSI.
82	**Bad Calibrations** *ShutdownMotor;* *ShutdownMainContactor;* *ShutdownEMBrake;* *ShutdownThrottle;* *FullBrake.*	1. Internal controller fault.	*Set:* Internal controller fault detection. *Clear:* Cycle KSI.
83	**Driver Supply** *ShutdownMotor;* *ShutdownMainContactor;* *ShutdownEMBrake;* *ShutdownThrottle;* *FullBrake.*	1. Internal controller fault in the voltage supply for the driver circuits.	*Set:* Internal controller fault detection. *Clear:* Cycle KSI.

Table 6 TROUBLESHOOTING CHART cont'd

CODE	PROGRAMMER LCD DISPLAY *EFFECT OF FAULT*	POSSIBLE CAUSE	SET / CLEAR CONDITIONS
87	**Motor Characterization Fault** *ShutdownMotor;* *ShutdownMainContactor;* *ShutdownEMBrake;* *ShutdownThrottle;* *FullBrake.*	1. Motor characterization failed during characterization process. See Monitor menu » Controller: Motor Characterization Error for cause: 0 = sequencing error. Normally caused by turning off Motor Characterization Test Enable before running the test. 1 = encoder signal seen but step size not auto-detected; set up Encoder Steps manually 2 = motor temp sensor fault 3 = motor temp hot cutback fault 4 = controller overtemp cutback fault 5 = controller undertemp cutback fault 6 = undervoltage cutback fault 7 = severe overvoltage fault 8 = encoder signal not seen, or one or both channels missing 9 = motor parameters out of characterization range 20 = Sin/Cos sensor not found 21 = phasing not detected 22 = Sin/Cos sensor characterization failure 23 = started characterization procedure while motor rotating.	*Set:* Motor characterization failed during the motor characterization process. Normally caused by turning off Motor_Characterization_Test_Enable before running test. Needs controller reset. *Clear:* Correct fault; cycle KSI, or VCL reset.
88	**Encoder Pulse Count Fault** *ShutdownMotor;* *ShutdownMainContactor;* *ShutdownEMBrake;* *ShutdownThrottle;* *ShutdownInterlock;* *ShutdownDriver1;* *ShutdownDriver2;* *ShutdownDriver3;* *ShutdownDriver4;* *ShutdownPD;* *FullBrake.*	1. Encoder Steps parameter does not match the actual motor encoder.	*Set:* Detected wrong setting of the Encoder Steps parameter. *Clear:* Ensure the Encoder Steps parameter matches the actual encoder; cycle KSI.
89	**Motor Type Fault** *ShutdownMotor;* *ShutdownMainContactor;* *ShutdownEMBrake;* *ShutdownThrottle;* *FullBrake.*	2. The Motor_Type parameter value is out of range.	*Set:* Motor_Type parameter is set to an illegal value. *Clear:* Set Motor_Type to correct value and cycle KSI.

Table 6 TROUBLESHOOTING CHART cont'd

CODE	PROGRAMMER LCD DISPLAY *EFFECT OF FAULT*	POSSIBLE CAUSE	SET / CLEAR CONDITIONS
91	**VCL/OS Mismatch** *ShutdownMotor;* *ShutdownMainContactor;* *ShutdownEMBrake;* *ShutdownThrottle;* *ShutdownInterlock;* *ShutdownDriver1;* *ShutdownDriver2;* *ShutdownDriver3;* *ShutdownDriver4;* *ShutdownPD;* *FullBrake.*	1. The VCL software in the controller does not match the OS software in the controller.	*Set:* VCL and OS software do not match; when KSI cycles, a check is made to verify that they match and a fault is issued when they do not. *Clear:* Download the correct VCL and OS software into the controller.
92	**EM Brake Failed to Set** *ShutdownEMBrake;* *ShutdownThrottle.* Position Hold is engaged when Interlock = On.	1. Vehicle movement sensed after the EM Brake has been commanded to set. 2. EM Brake will not hold the motor from rotating.	*Set:* After the EM Brake was commanded to set and time has elapsed to allow the brake to fully engage, vehicle movement has been sensed. *Clear:* 1. Activate the Throttle (EM Brake type 2). 2. Activate the Interlock (EM Brake type 1).
93	**Encoder LOS (Limited Operating Strategy)** Enter LOS control mode.	1. Limited Operating Strategy (LOS) control mode has been activated, as a result of either an Encoder Fault (Code 36) or a Stall Detected fault (Code 73). 2. Motor encoder failure. 3. Bad crimps or faulty wiring. 4. Vehicle is stalled.	*Set:* Encoder Fault (code 36) or Stall Detected (code 73) was activated, if parameter LOS Upon Encoder Fault = On and Interlock has been cycled, then the Encoder LOS (code 93) control mode is activated, allowing limited motor control. *Clear:* Cycle KSI or, if LOS mode was activated by the Stall Detected fault, clear by ensuring encoder senses proper operation, Motor RPM = 0, and Throttle Command = 0.
94	**Emer Rev Timeout** *ShutdownEMBrake;* *ShutdownThrottle.*	1. Emergency Reverse was activated and concluded because the EMR Timeout timer has expired. 2. The emergency reverse input is stuck On.	*Set:* Emergency Reverse was activated and ran until the EMR Timeout timer expired. *Clear:* Turn the emergency reverse input Off.
98	**Illegal Model Number** *ShutdownMotor;* *ShutdownMainContactor;* *ShutdownEMBrake;* *ShutdownThrottle;* *FullBrake.*	1. Model_Number variable contains illegal value. 2. Software and hardware do not match. 3. Controller defective.	*Set:* Illegal Model_Number variable; when KSI cycles, a check is made to confirm a legal Model_Number, and a fault is issued if one is not found. *Clear:* Download appropriate software for your controller model.
99	**Parameter Mismatch** *ShutdownMotor;* *ShutdownMainContactor;* *ShutdownEMBrake;* *ShutdownThrottle;* *FullBrake.*	1. Dual drive enabled on only one controller. 2. Incorrect position feedback type chosen for motor technology in use. 3. Dual drive is enabled in torque mode.	*Set:* When the Dual Drive software is enabled, the controller must be set to either Speed Mode Express or Speed Mode; otherwise this fault is set. Motor Techology=0 must be paired with Feedback Type=1, and Motor Technology=1 must be paired with Feedback Type=2; otherwise this fault is set. *Clear:* Adjust parameters to appropriate values and cycle KSI.

12 — MAINTENANCE

There are no user serviceable parts in Curtis E/SE controllers. No attempt should be made to open, repair, or otherwise modify the controller. Doing so may damage the controller and will void the warranty.

It is recommended that the controller and connections be kept clean and dry and that the controller's fault history file be checked and cleared periodically.

CLEANING

Periodically cleaning the controller exterior will help protect it against corrosion and possible electrical control problems created by dirt, grime, and chemicals that are part of the operating environment and that normally exist in battery powered systems.

⚠ CAUTION

When working around any battery powered system, proper safety precautions should be taken. These include, but are not limited to: proper training, wearing eye protection, and avoiding loose clothing and jewelry.

Use the following cleaning procedure for routine maintenance. Never use a high pressure washer to clean the controller.

1. Remove power by disconnecting the battery.
2. Discharge the capacitors in the controller by connecting a load (such as a contactor coil) across the controller's B+ and B– terminals.
3. Remove any dirt or corrosion from the power and signal connector areas. The controller should be wiped clean with a moist rag. Dry it before reconnecting the battery.
4. Make sure the connections are tight. Refer to Chapter 2, page 7–8, for maximum tightening torque specifications for the battery and motor connections.

FAULT HISTORY

The 1313 handheld or 1314 PC programmer can be used to access the controller's fault history file. The programmer will read out all the faults the controller has experienced since the last time the fault history file was cleared. Faults such as contactor faults may be the result of loose wires; contactor wiring should be carefully checked. Faults such as overtemperature may be caused by operator habits or by overloading.

After a problem has been diagnosed and corrected, it is a good idea to clear the fault history file. This allows the controller to accumulate a new file of faults. By checking the new fault history file at a later date, you can readily determine whether the problem was indeed fixed.

APPENDIX A

VEHICLE DESIGN CONSIDERATIONS REGARDING ELECTROMAGNETIC COMPATIBILITY (EMC) AND ELECTROSTATIC DISCHARGE (ESD)

DECOMMISSIONING AND RECYCLING THE CONTROLLER

ELECTROMAGNETIC COMPATIBILITY (EMC)

Electromagnetic compatibility (EMC) encompasses two areas: emissions and immunity. *Emissions* are radio frequency (RF) energy generated by a product. This energy has the potential to interfere with communications systems such as radio, television, cellular phones, dispatching, aircraft, etc. *Immunity* is the ability of a product to operate normally in the presence of RF energy.

EMC is ultimately a system design issue. Part of the EMC performance is designed into or inherent in each component; another part is designed into or inherent in end product characteristics such as shielding, wiring, and layout; and, finally, a portion is a function of the interactions between all these parts. The design techniques presented below can enhance EMC performance in products that use Curtis motor controllers.

Emissions

Signals with high frequency content can produce significant emissions if connected to a large enough radiating area (created by long wires spaced far apart). Contactor drivers and the motor drive output from Curtis controllers can contribute to RF emissions. Both types of output are pulse width modulated square waves with fast rise and fall times that are rich in harmonics. (Note: contactor drivers that are not modulated will not contribute to emissions.) The impact of these switching waveforms can be minimized by making the wires from the controller to the contactor or motor as short as possible and by placing the wires near each other (bundle contactor wires with Coil Return; bundle motor wires separately).

For applications requiring very low emissions, the solution may involve enclosing the controller, interconnect wires, contactors, and motor together in one shielded box. Emissions can also couple to battery supply leads and throttle circuit wires outside the box, so ferrite beads near the controller may also be required on these unshielded wires in some applications. It is best to keep the noisy signals as far as possible from sensitive wires.

Immunity

Immunity to radiated electric fields can be improved either by reducing overall circuit sensitivity or by keeping undesired signals away from this circuitry. The controller circuitry itself cannot be made less sensitive, since it must accurately detect and process low level signals from sensors such as the throttle potentiometer. Thus immunity is generally achieved by preventing the external RF energy from coupling into sensitive circuitry. This RF energy can get into the controller circuitry via conducted paths and radiated paths.

Conducted paths are created by the wires connected to the controller. These wires act as antennas and the amount of RF energy coupled into them is generally proportional to their length. The RF voltages and currents induced in each wire are applied to the controller pin to which the wire is connected. Curtis controllers include bypass capacitors on the printed circuit board's throttle wires to reduce the impact of this RF energy on the internal circuitry. In some applications, additional filtering in the form of ferrite beads may also be required on various wires to achieve desired performance levels.

Radiated paths are created when the controller circuitry is immersed in an external field. This coupling can be reduced by placing the controller as far as possible from the noise source or by enclosing the controller in a metal box. Some Curtis controllers are enclosed by a heatsink that also provides shielding around the controller circuitry, while others are partially shielded or unshielded. In some applications, the vehicle designer will need to mount the controller within a shielded box on the end product. The box can be constructed of just about any metal, although steel and aluminum are most commonly used.

Most coated plastics do not provide good shielding because the coatings are not true metals, but rather a mixture of small metal particles in a non-conductive binder. These relatively isolated particles may appear to be good based on a dc resistance measurement but do not provide adequate electron mobility to yield good shielding effectiveness. Electroless plating of plastic will yield a true metal and can thus be effective as an RF shield, but it is usually more expensive than the coatings.

A contiguous metal enclosure without any holes or seams, known as a Faraday cage, provides the best shielding for the given material and frequency. When a hole or holes are added, RF currents flowing on the outside surface of the shield must take a longer path to get around the hole than if the surface was contiguous. As more "bending" is required of these currents, more energy is coupled to the inside surface, and thus the shielding effectiveness is reduced. The reduction in shielding is a function of the longest linear dimension of a hole rather than the area. This concept is often applied where ventilation is necessary, in which case many small holes are preferable to a few larger ones.

Applying this same concept to seams or joints between adjacent pieces or segments of a shielded enclosure, it is important to minimize the open length of these seams. Seam length is the distance between points where good ohmic contact is made. This contact can be provided by solder, welds, or pressure contact. If pressure contact is used, attention must be paid to the corrosion characteristics of the shield material and any corrosion-resistant processes applied to the base material. If the ohmic contact itself is not continuous, the shielding effectiveness can be maximized by making the joints between adjacent pieces overlapping rather than abutted.

The shielding effectiveness of an enclosure is further reduced when a wire passes through a hole in the enclosure; RF energy on the wire from an external field is re-radiated into the interior of the enclosure. This coupling mechanism can be reduced by filtering the wire where it passes through the shield boundary.

Given the safety considerations involved in connecting electrical components to the chassis or frame in battery powered vehicles, such filtering will usually consist of a series inductor (or ferrite bead) rather than a shunt capacitor. If a capacitor is used, it must have a voltage rating and leakage characteristics that will allow the end product to meet applicable safety regulations.

The B+ (and B–, if applicable) wires that supply power to a control panel should be bundled with the other control wires to the panel so that all these wires are routed together. If the wires to the control panel are routed separately, a larger loop area is formed. Larger loop areas produce more efficient antennas which will result in decreased immunity performance.

Keep all low power I/O separate from the motor and battery leads. When this is not possible, cross them at right angles.

ELECTROSTATIC DISCHARGE (ESD)

Curtis motor controllers contain ESD-sensitive components, and it is therefore necessary to protect them from ESD (electrostatic discharge) damage. Most of the control lines have protection for moderate ESD events, but must be protected from damage if higher levels exist in a particular application.

ESD immunity is achieved either by providing sufficient distance between conductors and the ESD source so that a discharge will not occur, or by providing an intentional path for the discharge current such that the circuit is isolated from the electric and magnetic fields produced by the discharge. In general the guidelines presented above for increasing radiated immunity will also provide increased ESD immunity.

It is usually easier to prevent the discharge from occurring than to divert the current path. A fundamental technique for ESD prevention is to provide adequately thick insulation between all metal conductors and the outside environment so that the voltage gradient does not exceed the threshold required for a discharge to occur. If the current diversion approach is used, all exposed metal components must be grounded. The shielded enclosure, if properly grounded, can be used to divert the discharge current; it should be noted that the location of holes and seams can have a significant impact on ESD suppression. If the enclosure is not grounded, the path of the discharge current becomes more complex and less predictable, especially if holes and seams are involved. Some experimentation may be required to optimize the selection and placement of holes, wires, and grounding paths. Careful attention must be paid to the control panel design so that it can tolerate a static discharge.

MOV, transorbs, or other devices can be placed between B- and offending wires, plates, and touch points if ESD shock cannot be otherwise avoided.

DECOMMISSIONING AND RECYCLING THE CONTROLLER

The controller is intended for installation into an Original Equipment Manufacturer (OEM) vehicle. They are a component that has no function unless installed as part of the specific vehicles' electrical or electro-hydraulic control system.

For controller decommissioning and recycling:

1. Follow the OEM's vehicle decommissioning instructions.
2. Follow all applicable landfill directives or regulations for Electrical and Electronic Equipment (EEE) waste.

APPENDIX B

EN13849 COMPLIANCE

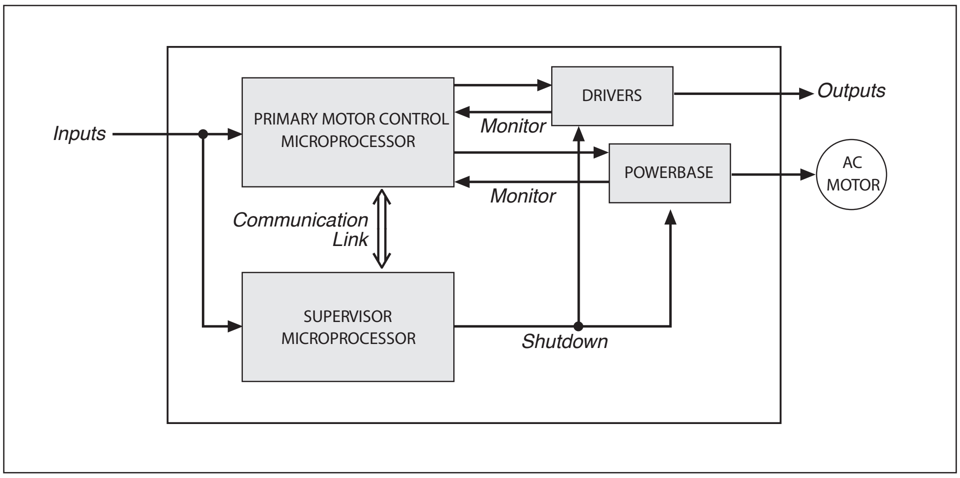
Since January 1, 2012, conformance to the European Machinery Directive has required that the Safety Related Parts of the Control System (SRPCS) be designed and verified upon the general principles outlined in EN13849. EN13849 supersedes the EN954 standard and expands upon it by requiring the determination of the safety Performance Level (PL) as a function of Designated Architecture plus Mean Time To Dangerous Failure (MTTFd), Common Cause Faults (CCF), and Diagnostic Coverage (DC). These figures are used by the OEM to calculate the overall PL for each of the safety functions of their vehicle or machine.

The OEM must determine the hazards that are applicable to their vehicle design, operation, and environment. Standards such as EN13849-1 provide guidelines that must be followed in order to achieve compliance. Some industries have developed further standards (called type-C standards) that refer to EN13849 and specifically outline the path to regulatory compliance. EN1175-1 is a type-C standard for battery-powered industrial trucks. Following a type-C standard provides a presumption of conformity to the Machinery Directive.

Curtis Enhanced AC Motor Controllers comply with these directives using advanced active supervisory techniques. The basic "watchdog" test circuits have been replaced with a Supervisor microcontroller that continuously tests the safety related parts of the control system; see the simplified block diagram in Figure B-1.

Figure B-1

Supervisory system in Curtis enhanced AC motor controllers.



The Supervisor and Primary motor control processors run diagnostic checks at startup and continuously during operation. At startup, the integrity of the code and EEPROM are ensured through CRC checksum calculations. RAM is pattern checked for proper read, write, and addressing. During operation, the arithmetic and logic processing unit of each micro is cyclically tested through dynamic stimulus and response. The operating system timing and task sequencing are continuously verified. Redundant input measurements are crosschecked over 30 times per second, and operational status information is passed between microprocessors to keep the system synchronized. Any faults in these startup tests, communication timing, crosschecks, or responses will command a safe shutdown of the controller, disabling the driver outputs and motor drive within 200 ms.

To mitigate the hazards typically found in machine operations, EN13849 requires that safety functions be defined; these must include all the input, logic, outputs, and power circuits that are involved in any potentially hazardous operation. Two safety functions are defined for Curtis Enhanced AC Motor Controllers: Uncommanded Powered Motion and Motor Braking Torque.

The Uncommanded Powered Motion safety function provides detection and safe shutdown in the following circumstances: faulted throttle; improper sequence of forward/reverse switches, throttle, and interlock; incorrect direction of travel; loss of speed control or limiting; uncommanded movement; or movement at start-up. The Braking Torque safety function provides detection and safe shutdown in the event of the loss of braking torque, position/hill hold, or emergency reverse.

Curtis has analyzed each safety function and calculated its Mean Time To Dangerous Failure (MTTFd) and Diagnostic Coverage (DC), and designed them against Common Cause Faults (CCF). The safety-related performance of the 1232E controller is summarized as follows:

Safety Function	Designated Architecture	MTTFd	DC	CCF	PL
Uncommanded Powered Motion	2	>40 yrs	>90%	Pass	d
Motor Braking Torque	2	>16 yrs	>90%	Pass	c

EN1175 specifies that traction and hydraulic electronic control systems must use **Designated Architecture 2** or greater. This design employs input, logic, and output circuits that are monitored and tested by independent circuits and software to ensure a high level of safety performance (up to PL=d).

Mean Time To Dangerous Failure (MTTFd) is related to the expected reliability of the safety related parts used in the controller. Only failures that can result in a dangerous situation are included in the calculation.

Diagnostic Coverage (DC) is a measure of the effectiveness of the control system's self-test and monitoring measures to detect failures and provide a safe shutdown.

Common Cause Faults (CCF) are so named because some faults within a controller can affect several systems. EN13849 provides a checklist of design techniques that should be followed to achieve sufficient mitigation of CCFs. The CCF value is a pass/fail criterion.

Performance Level (PL) categorizes the quality or effectiveness of a safety channel to reduce the potential risk caused by dangerous faults within the system with "a" being the lowest and "e" being the highest achievable performance.

APPENDIX C

PROGRAMMING DEVICES

Curtis programmers provide programming, diagnostic, and test capabilities for the controller. The power for operating the programmer is supplied by the host controller via a 4-pin connector. When the programmer powers up, it gathers information from the controller.

Two types of programming devices are available: the 1314 PC Programming Station and the 1313 handheld programmer. The Programming Station has the advantage of a large, easily read screen; on the other hand, the handheld programmer (with its 45×60mm screen) has the advantage of being more portable and hence convenient for making adjustments in the field.

Both programmers are available in User, Service, Dealer, and OEM versions. Each programmer can perform the actions available at its own level and the levels below that—a User-access programmer can operate at only the User level, whereas an OEM programmer has full access.

PC PROGRAMMING STATION (1314)

The Programming Station is an MS-Windows 32-bit application that runs on a standard Windows PC. Instructions for using the Programming Station are included with the software. In addition, the Curtis 1309 Interface box with a computer-side USB and controller-side 4-pin serial Molex connection is required for the 1314 PC Programmer.

HANDHELD PROGRAMMER (1313)

The 1313 handheld programmer is functionally equivalent to the PC Programming Station; operating instructions are provided in the 1313 manual. This programmer replaces the 1311, an earlier model with fewer functions.

PROGRAMMER FUNCTIONS

Programmer functions include:

Parameter adjustment — provides access to the individual programmable parameters.

Monitoring — presents real-time values during vehicle operation; these include all inputs and outputs.

Diagnostics and troubleshooting — presents diagnostic information, and also a means to clear the fault history file.

Programming — allows you to save/restore custom parameter settings.

Favorites — allows you to create shortcuts to your frequently-used adjustable parameters and monitor variables (1313 only).

APPENDIX D

CONTROLLER SPECIFICATIONS

Table D-1 SPECIFICATIONS: 1232E/SE, 1234E/SE, 1236E/SE, 1238E/SE CONTROLLERS

Nominal input voltage:	24 V, 24–36 V, 36–48 V, 48–80 V, 72–96 V

NOMINAL VOLTAGE	MINIMUM VOLTAGE	MAXIMUM VOLTAGE	BROWNOUT VOLTAGE
24 V	14 V	30 V	12 V
24–36 V	16.8 V	45 V	15 V
36–48 V	25.2 V	60 V	20 V
48–80 V	33.6 V	105 V	20 V
72–96 V	50.4 V	120 V	30 V

PWM operating frequency:	10 kHz	
Maximum encoder frequency:	10 kHz	
Maximum controller output frequency:	450 Hz	
Electrical isolation to heatsink:	500 V ac (minimum)	
Storage ambient temperature range:	–40°C to 95°C (–40°F to 203°F)	
Operating ambient temperature range:	–40°C to 50°C (–40°F to 122°F)	
Thermal cutback:	Controller linearly reduces maximum current limit with an internal heatsink temperature from 85°C (185°F) to 95°C (203°F); complete cutoff occurs above 95°C (203°F) and below –40°C (–40°F)	
Design life:	*1238E-75XX and 1238E-76XX*: 5,000 hours *All other models*: 20,000 hours	
Operating duration at maximum current:	2 minutes minimum (unless otherwise noted), with initial temperature of 25°C and no additional external heatsink	
Package environmental rating:	IP65 per IEC529; compliance requires AMPSEAL 35-pin connector header	
Weight:	*1232E*: 1.70 kg *1234E*: 2.84 kg *1236E*: 4.12 kg *1238E*: 6.82 kg	*1232SE*: 1.92 kg *1234SE*: 3.12 kg *1236SE*: 3.79 kg *1238SE*: 6.00 kg
Dimensions, W×L×H:	*1232E*: 140 × 180 × 71 mm *1234E*: 155 × 212 × 75 mm *1236E*: 165 × 232 × 85 mm *1238E*: 275 × 232 × 85 mm	*1232SE*: 140 × 180 × 74 mm *1234SE*: 155 × 212 × 79 mm *1236SE*: 165 × 232 × 85 mm *1238SE*: 275 × 232 × 85 mm
EMC:	Designed to the requirements of EN 12895:2000	
Safety:	Designed to the requirements of EN 1175-1:1998 + A1:2010 and EN 13849-1:2008 Category 2	
UL:	UL recognized component per UL583	

Note: Regulatory compliance of the complete vehicle system with the controller installed is the responsibility of the OEM.

Table D-1 SPECIFICATIONS: 1232E/SE, 1234E/SE, 1236E/SE, 1238E/SE CONTROLLERS, Cont'd

MODEL CHART				
MODEI NUMBER	NOMINAL BATTERY VOLTAGE (V)	MAXIMUM CURRENT (A)	S2–60 MINUTE CONTINUOUS CURRENT (A)	CONTINUOUS CURRENT FOR DESIGN LIFE (A)
1232E-21XX	24	180	90	80
1232E-23XX	24	250	125	100
1232E-51XX	36–48	150	75	79
1232E-52XX	36–48	200	100	90
1232E-62XX	48–80	175	80	45
1232E-72XX	72–96	175	80	50
1234E-23XX	24	350	175	160
1234E-52XX	36–48	275	135	90
1234E-53XX	36–48	350	175	90
1234E-62XX	48–80	250	110	60
1236E-44XX	24–36	400	175	175
1236E-45XX	24–36	500	240	210
1236E-54XX	36–48	450	205	210
1236E-55XX	36–48	550	250	140
1236E-64XX	48–80	350 (1 min)	100	100
1238E-46XX	24–36	650	300	325
1238E-48XX	24–36	800	355	365
1238E-56XX	36–48	650	295	325
1238E-64XX	48–80	450	155	175
1238E-65XX	48–80	550	190	175
1238E-66XX	48–80	650 (1 min)	195	175
1238E-75XX	72–96	550	175	175
1238E-76XX	72–96	650	200	175
1232SE-24XX	24	375	185	160
1232SE-53XX	36–48	350	175	160
1234SE-45XX	24–36	500	235	210
1234SE-54XX	36–48	450	215	210
1234SE-63XX	48–80	350	149	175
1236SE-46XX	24–36	650	285	220
1236SE-56XX	36–48	600	260	210
1236SE-65XX	48–80	450	185	175
1238SE-49XX	24–36	1000*	425	376

Notes: All current ratings are rms values per motor phase.

***S2–60 minute current** is the typical current achievable before thermal cutback occurs, with an ambient temperature of 25°C and the controller mounted to a 6 mm thick vertical steel plate with 6 km/h (1.7 m/s) airflow perpendicular to the plate.*

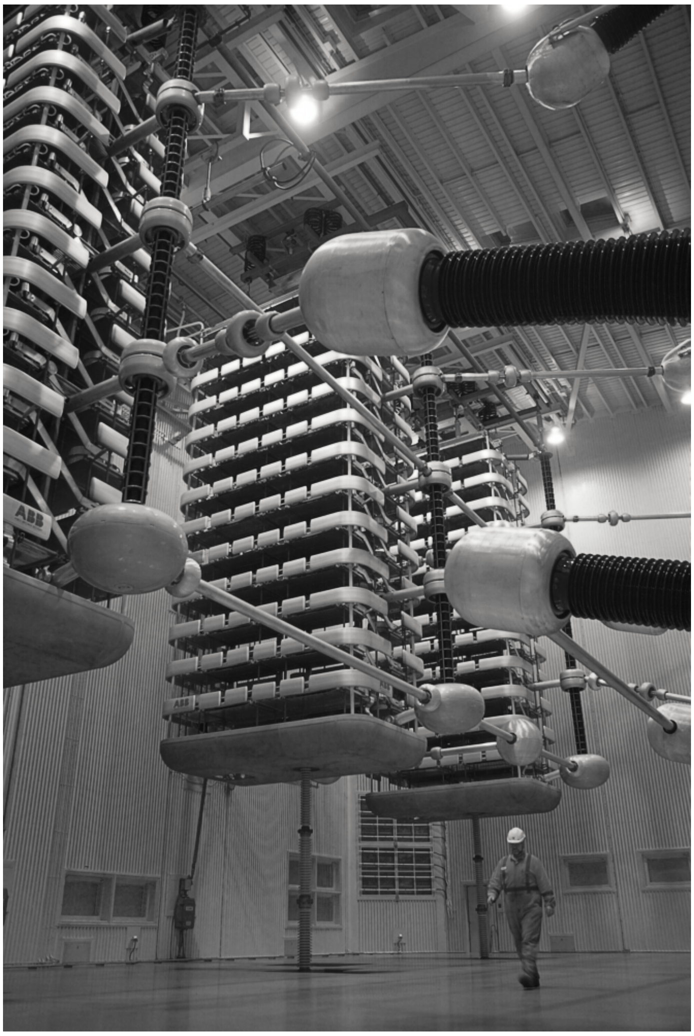
***Continuous current for design life** is the maximum long-term current, at an internal heatsink long-term temperature of 70°C (158°F), at which the controller will achieve its design life. These numbers are often calculated for a given application by determining an rms duty cycle current and heatsink temperature. For applications that exceed this, please contact your Curtis distributor or support engineer.*

**1238SE-49XX. Please contact your Curtis distributor or support engineer regarding the duty-cycle of this controller.*

E “Kraftelektronikk og elektriske maskiner” by Trond Østrem

Trond Østrem

Kraftelektronikk og elektriske maskiner



Forord

Dette kompendiet danner grunnlag for fagene ETE-2602 Strømrettere og transformatorer og ETE-2603 Roterende elektriske maskiner. Det har vært utviklet av undertegnede over mange år og begynner å nå sin endelige form. Mange feil har blitt rettet underveis, og mange flere ligger sikkert skjult i tekst og formler. En stor takk til enhver årvåken leser som oppdager feil og gir tilbakemeldinger om det. Hvis det er emner som er dårlig eller utydelig forklart, vil jeg gjerne ha tilbakemeldinger på det også. Det er sikkert temaer som burde vært tatt med, og andre ting kunne trolig vært utelatt.

Kompendiet trykkes ikke opp, men er tilgjengelig elektronisk på Canvas.

Det fins øvingsoppgaver for hvert kapittel, med fasit på regneoppgavene bakerst i kompendiet. Kombinert med øvinger og tidligere eksamener skulle det gi et godt grunnlag for å forstå og beherske teorien rundt kraftelektronikk og elektriske maskiner.
Lykke til med faget!

Narvik 4. januar 2021
Trond Østrem

Innhold

Nomenklatur

Kapittel 1

Symbol	Størrelse	Benevnelse
H	Magnetisk feltstyrke	$\mathrm{A/\,m}$
ℓ	Midlere lengde av flukslinje	m
N	Vindingstall	
B	Flukstetthet	T
μ	Permeabilitet	$\mathrm{H/\,m}$
μ_0	Permeabilitet for luft (vakuum)	$4\pi{\cdot}10^{-7}\ \mathrm{H/\,m}$
μ_r	Relativ permeabilitet	
ϕ	Fluks	Wb
A	Kjernetverrsnitt	m^2
F_m	Magnetomotorisk kraft (mmk)	$\mathrm{At\,(\,A)}$
R_m	Reluktans	$1/\,\mathrm{H}$
P_m	Permeans	H
L	Induktans	H
E eller e	Indusert spenning	V
ψ	Spolefluks	$\mathrm{Wbt\,(\,Wb)}$

Kapittel 2

Symbol	Størrelse	Benevnelse
W	Tapsenergi	J
ΔP	Totale tap	W
T	Periodetid	s
f	Frekvens	Hz

Kapittel 3

Symbol	Størrelse	Benevnelse
W	Energi	J
ΔP	Totale tap	W
P_1	Tilført effekt	W
P_2	Avgitt effekt	W
P_0	Tomgangstap	W
P_b	Belastningstap	W
P_{hy}	Hysteresetap	W
P_{vi}	Virvelstrømstap	W
P_{vi}	Friksjonstap	W
P_{DC}	Likestrømstap	W
P_{till}	Tilleggstap	W
P_{sw}	Svitsjetap	W
ϑ	Absolutt temperatur	$^\circ\mathrm{C}$
θ	Overtemperatur	$^\circ$
c	Spesifikk varmekapasitet	$\mathrm{J/\,kg\cdot\ K}$
m	Maskinmasse	kg
α	Varmeovergangstall	$\mathrm{W/\,m^2\cdot\ K}$
A	Varmeavgivende flate	m^2
T	Termisk tidskonstant	min

Kapittel 4

Symbol	Størrelse	Benevnelse
U_v	Nettspenning	V
U_m	Amplitudeverdi av nettspenningen	V
U_L	Lastspenning	V
α	Styrevinkel	° eller rad
$U_{control}$	Styrespenning (amplitudeverdi)	V
U_{tri}	Triangelspenning (amplitudeverdi)	V
U_d	Likespenning	V

Kapittel 5

Primærsiden

Symbol	Størrelse	Benevnelse
U_1 eller U_L	Primær klemmespenning	V
U_{1f}	Primær fasespenning	V
N_1	Primært vindingstall	
E_1	Indusert primærspenning	V
E_{1f}	Indusert primær fasespenning	V
I_1	Primær strøm	A
R_1	Primær viklingsresistans	Ω
X_1	Primær lekkreaktans	Ω
$R_k{}'$	Kortslutningsresistans sett fra primærsiden	Ω
$X_k{}'$	Kortslutningsreaktans sett fra primærsiden	Ω
$R_k{}''$	Kortslutningsresistans sett fra sekundærsiden	Ω
$X_k{}''$ eller X_t	Kortslutningsreaktans sett fra sekundærsiden	Ω
P_1	Tilført aktiv effekt	W
Q_1	Tilført reaktiv effekt	VAr
S_1	Tilført tilsynelatende effekt	V A

Sekundærsiden

Symbol	Størrelse	Benevnelse
U_2	Sekundær klemmespenning	V
U_{2f} eller U_v	Sekundær fasespenning	V
$U_2{}'$	Sekundær klemmespenning sett fra primærsiden	V
$U_{2f}{}'$	Sekundær fasespenning sett fra primærsiden	V
N_2	Sekundært vindingstall	
E_2	Indusert sekundærspenning	V
E_{2f}	Indusert sekundær fasespenning	V
$E_2{}'$	Indusert sekundærspenning sett fra primærsiden	V
$E_{2f}{}'$	Indusert sekundær fasespenning sett fra primærsiden	V
I_2	Sekundær strøm	A
$I_2{}'$	Sekundær strøm sett fra primærsiden	A
R_2	Sekundær viklingsresistans	Ω
X_2	Sekundær lekkreaktans	Ω
$R_2{}'$	Sekundær viklingsresistans sett fra primærsiden	Ω
$X_2{}'$	Sekundær lekkreaktans sett fra primærsiden	Ω
P_2	Avgitt aktiv effekt	W
Q_2	Avgitt reaktiv effekt	VAr
S_2	Avgitt tilsynelatende effekt	V A

Tomgang

Symbol	Størrelse	Benevnelse
I_0	Tomgangsstrøm	A
I_{0p}	Tomgangsstrømmens aktive komponent (tap)	A
I_{0q}	Tomgangsstrømmens reaktive komponent (magnetisering)	A
R_0	Ekvivalent tomgangsresistans (jerntap)	Ω
X_0	Ekvivalent tomgangsreaktans (fellesfluks)	Ω
P_0 eller P_{Fe}	Tomgangstap (jerntap)	W
P_{hy}	Hysteresetap	W
P_{vi}	Virvelstrømstap	W

Andre størrelser

Symbol	Størrelse	Benevnelse
ϕ	Fellesfluks	Wb
$\phi_{\max}$	Fellesfluksens amplitude	Wb
B	Flukstetthet	T
A	Kjernetverrsnitt	m^2
ΔU	Spenningsfall	V
$\Delta u\%$	Relativt spenningsfall	
ΔU_k	Spenningsfall ved kortslutning	V
n	Belastningsgrad	
n_m	Optimal belastningsgrad	
e_r	Relativt resistansspenningsfall	
e_x	Relativt reaktansspenningsfall	
e_z eller e_k	Relativt kortslutningsspenningsfall	
ΔP	Totale tap	W
P_b eller P_{Cu}	Belastningstap (kobbertap)	W
P_{DC}	Likestrømstap	W
P_{till}	Tilleggstap	W
P_{b75}	Belastningstap ved driftstemperatur	W
ϑ	Omgivelsestemperatur	$^\circ\mathrm{C}$
η	Virkningsgrad	
I_u	Utjevningsstrøm ved parallellkobling	A
S_g	Gjennomgangseffekt	$\mathrm{V\,A}$
S_e	Egeneffekt	$\mathrm{V\,A}$

Kapittel 6

Diode- og tyristor-omformere

Symbol	Størrelse	Benevnelse
U_{di0}	Likespenning ved tomgang	V
U_v	Sekundær linjespenning (enfase) eller fasespenning (trefase)	V
U_L	Primær linjespenning	V
$U_{s\ \max}$	Maksimal sperrespenning	V
I_d	Likestrøm	A
I_v	Sekundær vekselstrøm	A
I_L	Primær vekselstrøm	A
α	Styrevinkel likerettere	° eller rad
U_{dx}	Kommuteringsspenningsfall	V
X_t eller $X_k{}''$	Transformatorens kortslutningsreaktans	Ω
U_d	Likespenning	V
U_{rippel}	Ripelspenning (topp til topp)	V
f_{rippel}	Rippelfrekvens	Hz
β	Styrevinkel vekselrettere	° eller rad
γ	Kommuteringsmargin	° eller rad

Aktive omformere

Symbol	Størrelse	Benevnelse
U_d	Likespenning	V
U_v	Vekselspenning omformer	V
U_L	Nettspenning	V
T_{sw}	Svitsjeperiode	s
f_{sw}	Svitsjefrekvens	Hz
t_{on}	På-tid	s
d	Pulsbreddeforhold (duty cycle)	
$U_{control}$	Kontrollspenning (amplitude)	V
U_{tri}	Triangelspenning (amplitude)	V
I_{rippel}	Rippelstrøm (topp til topp)	A
U_α	Spenningsvektorens reelle del	V
U_β	Spenningsvektorens imaginære del	V
I_α	Strømvektorens reelle del	A
I_β	Strømvektorens imaginære del	A
U_d	Spenningsvektorens direkte komponent	V
U_q	Spenningsvektorens kvadratur-komponent	V
I_d	Strømvektorens direkte komponent	A
I_q	Strømvektorens kvadratur-komponent	A
θ	Referansevinkel for nettspenningen	° eller rad

DC-DC omformere

Symbol	Størrelse	Benevnelse
t_{on}	På-tid	s
T_{sw}	Svitsjeperiode	s
d	Pulsbreddeforhold (duty cycle)	
U_d	Inngangsspenning	V
U_o	Utgangsspenning	V
I_d	Inngangsstrøm	A
I_o	Utgangsstrøm	A

Kapittel 8

Symbol	Størrelse	Benevnelse
Indeks $+$	Pluss-komponent	$\mathrm{V},\ \mathrm{A},\ \Omega$
Indeks $-$	Minus-komponent	$\mathrm{V},\ \mathrm{A},\ \Omega$
Indeks 0	Null-komponent	$\mathrm{V},\ \mathrm{A},\ \Omega$
α	Operator som dreier vektor $120\,^{\circ}$	
α^2	Operator som dreier vektor $-120\,^{\circ}$	

Kapittel 9

Symbol	Størrelse	Benevnelse
T_{el}	Drivmoment	$\mathrm{N\,m}$
T_{last}	Lastens bremsemoment	$\mathrm{N\,m}$
T_{fr}	Friksjonsmoment	$\mathrm{N\,m}$
$T_{last}\,'$	Resulterende bremsemoment	$\mathrm{N\,m}$
n	Turtall	o/min
ω	Vinkelhastighet	$\mathrm{rad/\,s}$
J	Treghetsmoment	$\mathrm{kg\,m^2}$
P_{last}	Lasteffekt	W
θ	Vinkelendring	rad
r	Radius	m
F	Trekkraft, snordrag	N
J'	Lastens treghetsmoment sett fra motorakselen	$\mathrm{kg\,m^2}$
m	Masse	kg
v	Lineær hastighet	$\mathrm{m/\,s}$
F_{el}	Lineær kraftvirkning fra motor	N
F_{last}	Lineær kraftvirkning fra last	N
F_{fr}	Lineær kraftvirkning fra friksjon	N
$F_{last}\,'$	Resulterende kraftvirkning fra last	N
P_{el}	Motoreffekt	W
P_{fr}	Friksjonstap	W

Kapittel 10

Turtall, frekvens, dreiemoment, fluks, indusert spenning:

Symbol	Størrelse	Benevnelse
n_s	Synkront turtall	o/min
f_1	Statorfrekvens	Hz
f_2	Rotorfrekvens	Hz
p	antall polpar	
n_r eller n	Rotorturtall	o/min
ω_s	Synkron vinkelhastighet	$\mathrm{rad/s}$
ω_s	Rotors vinkelhastighet	$\mathrm{rad/s}$
E	Indusert spenning	V
B	Flukstetthet	T
ℓ	Effektiv lederlengde	m
v	Hastighet vinkelrett på feltet	$\mathrm{m/s}$
F	Kraftvirkning på rotorleder	N
T_{el} eller T	Drivmoment	$\mathrm{N\,m}$
E_{1f}	Indusert fasespenning i stator	V
E_{2f}	Indusert fasespenning i stillestående rotor	V
N_1	Effektivt vindingstall per statorfase	
N_2	Effektivt vindingstall per rotorfase	
$\phi_{\max}$	Maksimal luftgapsfluks per poldeling	Wb
R_1	Viklingsresistans i stator	Ω
X_1	Lekkreaktans i stator	Ω
R_0	Ekvivalent tomgangsresistans (jerntap og friksjon)	Ω
X_0	Ekvivalent tomgangsreaktans (luftgapsfelt)	Ω
R_2	Rotorresistans	Ω
$R_{2,ytre}$	Sleperingsmotstand	Ω
X_2	Lekkreaktans i stillestående rotor	Ω
Indeks $'$	Rotorstørrelse sett fra statorsiden	

Sakking, effekt, moment-turtallskarakteristikk, virkningsgrad:

Symbol	Størrelse	Benevnelse
s	Relativ sakking	o/min
Δn	Absolutt sakking	
P_1	Tilført aktiv effekt	W
P_{Fe}	Jerntap	W
P_{12}	Luftgapseffekt	W
P_2	Avgitt mekanisk effekt	W
ΔP_2	Rotortap	W
I_2	Rotorstrøm	A
s_m	Kippsakking	
T_{max}	Kippmoment	$\mathrm{N\,m}$
T_{start}	Startmoment (drivmoment ved stillstand)	$\mathrm{N\,m}$
U_1	Klemmespenning (statorspenning)	V
P_0	Tomgangstap	W
P_{Fr}	Friksjonstap	W
P_b	Belastningstap	W
$P_{\text{børste}}$	Børstetap	W
P_{till}	Tilleggstap	W
ΔP	Samlede tap	W
η	Virkningsgrad	

Kapittel 11

Symbol	Størrelse	Benevnelse
n_s	Synkront turtall	o/min
ω_s	Synkron vinkelhastighet	$\mathrm{rad/s}$
f	Nettfrekvens	Hz
p	Antall polpar	
B	Flukstetthet	T
ℓ	lederlengde	m
v	Hastighet vinkelrett på feltet	$\mathrm{m/s}$
N_{eff}	Effektivt vindingstall	
$\phi_{\max}$	Maksimal luftgapsfluks	Wb
ϕ_m	Hovedfelt	Wb
I_m	Magnetiseringsstrøm	A
ϕ_a	Ankerfelt	Wb
I_a	Ankerstrøm	A
ϕ_{ag}	Luftgapsfelt	Wb
X_l	Lekkreaktans i ankeret	Ω
R_a	Ankerresistans	Ω
X_d	Synkronreaktans	Ω
X_a	Ankerreaktans	Ω
E_f	Indusert fasespenning	V
E	Indusert spenning	V
E_{0f}	Indusert fasespenning ved tomgang	V
E_0	Indusert tomgangsspenning	V
U_f	Fasespenning nett	V
U	Nettspenning	V
β	Lastvinkel, polhjulsvinkel	$^\circ$, rad
P	Avgitt aktiv effekt	W
Q	Avgitt reaktiv effekt	VAr
$P_{\max}$	Maksimal avgitt effekt	W
$T_{\max}$	Maksimalt bremsemoment	$\mathrm{N\,m}$

Kapittel 12

Symbol	Størrelse	Benevnelse
E	Rotasjonsndusert spenning	V
B	Flukstetthet	T
ℓ	lederlengde	m
v	Hastighet vinkelrett på feltet	$\mathrm{m/s}$
n	Turtall	o/min
I_a	Ankerstrøm	A
R_a	Ankerresistans	Ω
U	Klemmespenning	V
I_m	Feltstrøm	A
k_E, k_T	Maskinkonstanter	
E_{AC}	Vekselstrømsindusert spenning	V
f	Nettfrekvens	Hz
N	Vindingstall i ankervinding	
$\phi_{\max}$	Maksimal ankerfluks	Wb

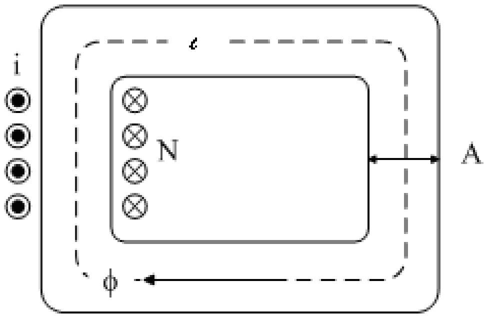
1 Grunnleggende elektromagnetisme

1.1 Grunnleggende magnetiske størrelser

De grunnleggende magnetiske størrelsene er listet opp i tabell 1.1. Figur 1.1 viser plasseringen av noen av disse i en magnetisk krets, en spole med jernkjerne.

Tabell 1.1: Grunnleggende magnetiske størrelser

Størrelse	Symbol	Benevnelse
Strømstyrke	i	A
Magnetisk feltstyrke	H	A/m
Midlere lengde av flukslinje	ℓ	m
Vindingstall	N	ubenevnt
Flukstetthet	B	Wb/m^2 eller T
Permeabilitet	μ	H/m
Permeabilitet for luft (vakuum)	μ_0	$4\pi \cdot 10^{-7}$ H/m
Relativ permeabilitet	μ_r	ubenevnt
Fluks	ϕ	Wb
Kjernetverrsnitt	A	m^2
Magnetomotorisk kraft (mmk)	F_m	At (A)
Reluktans	R_m	1/H
Permeans (induktans)	P_m (L)	H



Figur 1.1: Magnetisk krets

Magnetisk feltstyrke:

$$H = \frac{Ni}{\ell} \tag{1.1}$$

Flukstetthet:

$$B = \mu H \tag{1.2}$$

Permeabilitet (magnetisk ledningsevne):

$$\mu = \mu_0 \mu_r \tag{1.3}$$

Den relative permeabiliteten for luft er lik $1,0$, for støpejern kan den være opptil 800, for smijern opptil 3000, for transformatorblikk opptil 8000 og for enkelte materialer (ultraperm - en nikkel/jern-legering) helt opptil 300000. For luft er μ_r konstant, men for ferromagnetiske materialer avtar den når feltstyrken blir høy nok. Årsaken er at når alle molekylmagnetene har orientert seg langs feltet, kan ikke materialet bidra til ytterligere økning av feltstyrken. Materialet går i magnetisk metning.

Fluks (magnetisk ”strøm”):

$$\phi = BA \tag{1.4}$$

Magnetomotorisk kraft (amperevindinger):

$$F_m = Ni \tag{1.5}$$

Reluktans (magnetisk motstand):

$$R_m = \frac{\ell}{\mu A} \tag{1.6}$$

Permeans (induktans):

$$P_m = L = \frac{1}{R_m} = \frac{\mu A}{\ell} \tag{1.7}$$

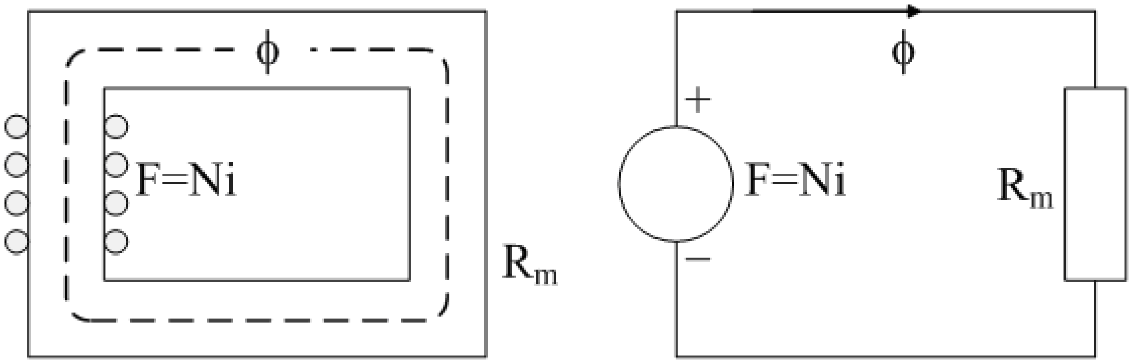
Permeans er i likhet med permeabilitet en størrelse som angir magnetisk ledningsevne. Forskjellen er at permeabilitet gir ledningsevne for et materiale, mens permeans gir ledningsevnen for en gitt krets, hvor det tas hensyn til tverrsnitt og flukslengde, som det fremgår av 1.7 og figur 1.1.

Forhold mellom fluks, reluktans og magnetomotorisk kraft:

$$\phi = \frac{F_m}{R_m} \tag{1.8}$$

1.2 Magnetiske kretser

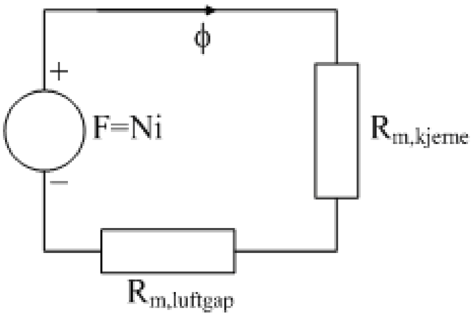
Formel (1.8) kalles Amperes lov, poplært kalt Ohms lov for magnetiske kretser. Den magnetomotoriske kraften F_m tilsvarer en elektrisk spenning, reluktansen R_m tilsvarer resistansen, og fluksen ϕ tilsvarer strømmen i kretsen. Figur 1.2 viser hvordan kretsen i figur 1.1 kan omgjøres til en ekvivalent magnetisk krets.



Figur 1.2: Ekvivalent magnetisk krets

Eksempel 1 *En spole med jernkjerne har* 200 *vindinger, kjernetverrsnittet er* 100 *cm*^{2}*, gjennomsnittlig flukslengde er* $139,8$ *cm. I tillegg kommer et luftgap på* 2 *mm. Kjernen har en relativ permeabilitet på* 2000*. Tegn en ekvivalent krets. Beregn fluks og flukstetthet når spolen påtrykkes en strøm på* 12 *A.*

Løsning:
Den ekvivalente kretsen er vist i figur 1.3.



Figur 1.3: Ekvivalent magnetisk krets

Permeabiliteten for kjernen er

$$\mu_{kjerne} = \mu_0\mu_r = 4\pi \cdot 10^{-7} \cdot 2000 = 2,51 \cdot 10^{-3} \text{ H/m}$$

Reluktansen i kjernen er

$$R_{m,kjerne} = \frac{\ell_{kjerne}}{\mu_{kjerne}A} = \frac{1,398}{0,00251 \cdot 0,01} = 55,6mH^{-1}$$

Reluktansen i luftgapet er

$$R_{m,\text{luftgap}} = \frac{\ell_{\text{luftgap}}}{\mu_0 A} = \frac{0,002}{4\pi \cdot 10^{-7} \cdot 0,01} = 159000 \text{ H}^{-1} = 159 \text{ mH}^{-1}$$

Den samlede reluktansen blir da

$$R_{m,total} = R_{m,kjerne} + R_{m,luftgap} = 215000 \text{ H}^{-1}$$

Den magnetomotoriske kraften er

$$F_m = Ni = 200 \cdot 12 = 2400 \text{ At}$$

Dermed blir fluksen

$$\phi = \frac{F_m}{R_{m,total}} = \frac{2400}{215000} = 11,2 \text{ mWb}$$

Og flukstettheten er

$$B = \frac{\phi}{A} = \frac{0,0112}{0,01} = 1,12 \text{ T}$$

Det er verd å merke seg at den ekvivalente kretsen kun gjelder så lenge kjernen ikke går i metning. Da vil nemlig reluktansen R_m bli lavere, og formel (1.8) gjelder ikke lenger.

1.3 Forhold mellom strøm, spenning og fluks i en spole

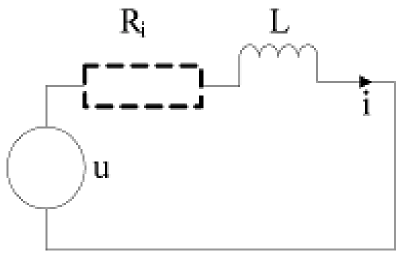
Faradays lov:
Polariteten til den induserte spenningen er slik at den vil forsøke å skape en strøm i kretsen som motvirker endringen i magnetfeltet; det vil si at den induserte strømmen vil skape et nytt felt som motvirker det opprinnelige.
Dette kan uttrykkes ved følgende formel:

$$e = N\frac{d\phi}{dt} \tag{1.9}$$

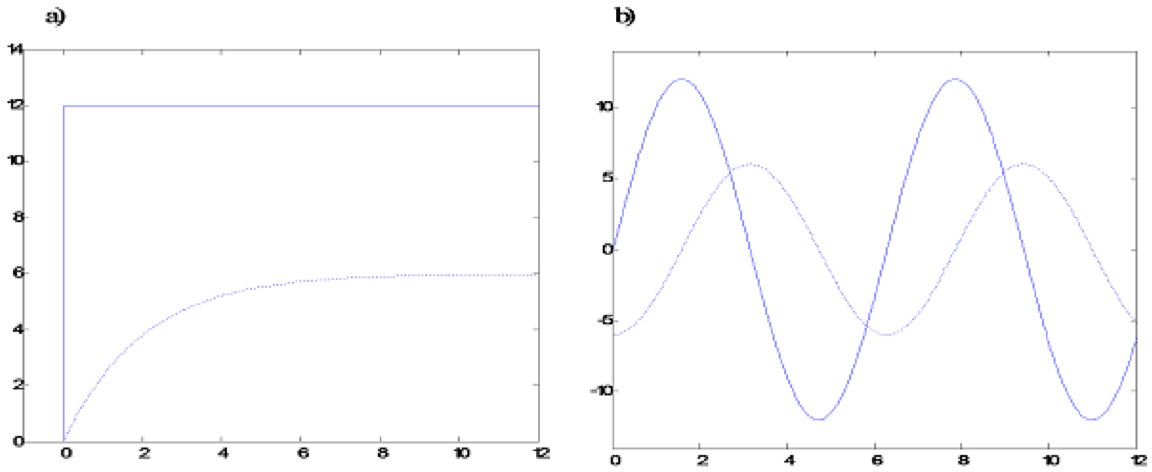
Som gir uttrykk for at indusert spenning e er proporsjonal med fluksendringen per tidsenhet.
Indusert spenning i en spole kan også uttrykket som en funksjon av endring i spolestrømmen:

$$e = L\frac{di}{dt} \tag{1.10}$$

hvor L er induktansen i spolen. Induktans er ekvivalent med permeans, og benevnelsen er Henry (H). Dersom kretsen i figur 1.4 påtrykkes et spenningssprang, vil strømmen øke eksponensielt mot en stasjonær verdi som vist i figur 1.5a. Dersom kretsen tilføres en sinusformet vekselspenning, vil strømmen også være sinusformet, men ligge $90°$ etter spenningen, som vist i figur 1.5b.



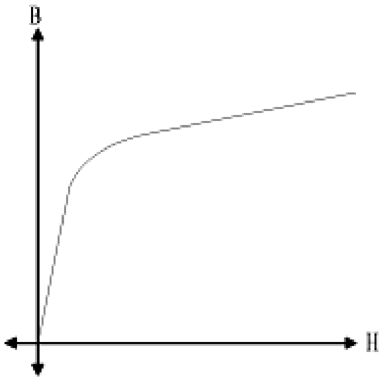
Figur 1.4: Krets med spenningskilde, indre resistans og spole



Figur 1.5: Spenning (heltrukket linje) og strøm (stiplet linje) ved a) spenningssprang og b) sinusformet spenning over en spole

1.4 Metning og hysterese

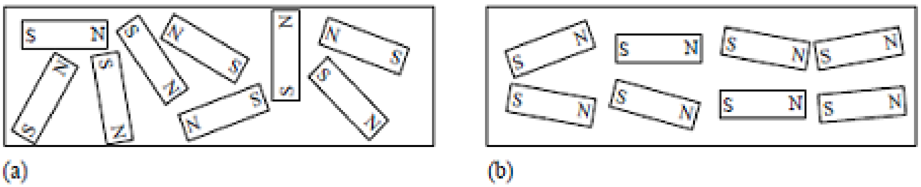
Som tidligere nevnt, vil et ferromagnetisk materiale gå i metning når den magnetiske feltstyrken når et visst nivå. Dette innebærer at flukstettheten ikke øker lineært ved økende feltstyrke. Dette forholdet er illustrert i figur 1.6.



Figur 1.6: Metning i kjernemateriale

Årsaken er at når alle molekylmagnetene har orientert seg langs feltet, vil ikke materialet i seg selv lenger gi noe bidrag til økning i flukstettheten.

Når feltet forsvinner, vil de fleste molekylmagnetene orientere seg tilfeldig, men noen vil beholde posisjonen. Resultatet er at materialet beholder en viss restmagnetisme, også kalt remanens (B_r). Figur 1.7 viser hvordan molekylmagnetene skaper remanens i et bløtt materiale (a) og i et hardt materiale (b).



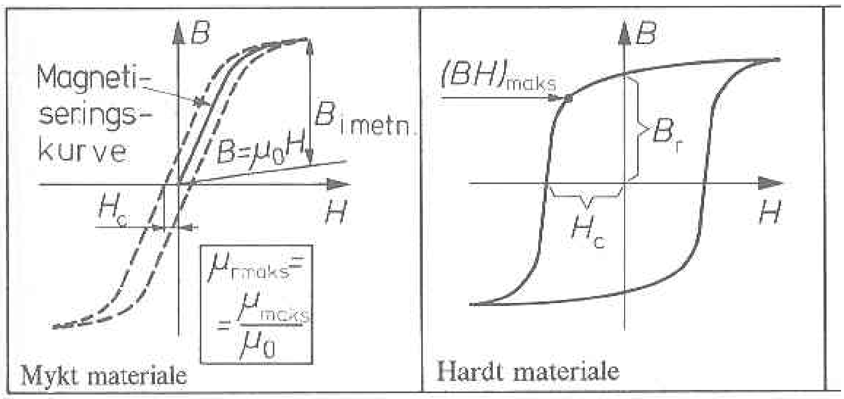
Figur 1.7: Remanens. (a) Bløtt materiale. (b) Hardt materiale

For å fjerne denne restmagnetismen, må materialet påtrykkes et visst felt med motsatt polaritet, den såkalte koersitivkraften (H_c). Denne "tregheten" i det magnetiske materialet kalles hysterese og er vist på figur 1.8. Figur 1.8a viser et bløtt materiale som har liten restmagnetisme, mens figur 1.8b viser et hardt materiale med stor restmagnetisme.

Man må altså tilføre ekstra magnetisk energi for å bringe materialet tilbake til sin opprinnelige tilstand. I en vekselstrømskrets vil også magnetfeltet skifte polaritet, og kjernematerialets hysterese gir et tap i kretsen. Hysteresetapet vil være proporsjonalt med arealet av hysteresesløyfa. Denne tapseffekten omdannes til varme og skaper en temperaturøkning i kjerna.

1.5 Permanentmagneter

Hysteresesløyfa til høyre i figur 1.8 viser en stor restmagnetisme B_r når feltet H er slått av. Harde materialer som utsettes for et kraftig felt, blir med andre ord permanentmagneter. De trenger ingen strømførende vikling, siden fluksen er vedvarende. Permanentmagneter brukes i en del motortyper (små DC-motorer, permanentmagnet synkronmaskiner m.m.).



Figur 1.8: Hysteresesløyfer for bløtt materiale (til venstre) og hardt materiale (til høyre)

1.6 Koblede spoler

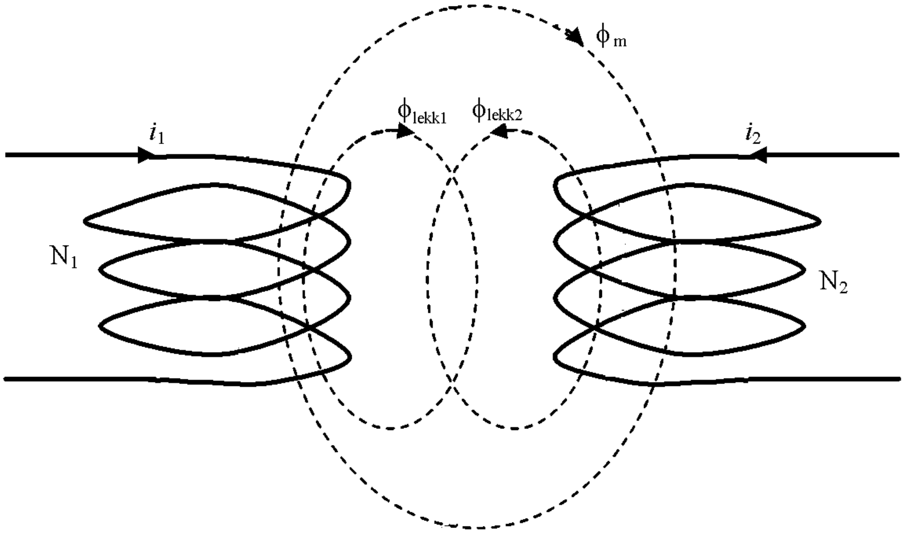
To spoler som står så nær hverandre at magnetfeltene virker inn på hverandre eller som er plassert på felles kjerne, kalles koblede spoler. Vi innfører begrepet spolefluks, også kalt fluksforslyngninger:

$$\psi = N\phi \tag{1.11}$$

som er definert som fluks multiplisert med vindingstall i en spole. Spolefluks kan også uttrykkes som strøm multiplisert med induktans:

$$\psi = Li \tag{1.12}$$

Figur 1.9 viser hvordan flukslinjene i to spoler delvis virker inn på hverandre. ϕ_{lekk1} er den fluksen fra spole 1 som ikke går gjennom spole 2, mens ϕ_m er summen av den fluksen fra spole 1 som virker inn på spole 2 og fra spole 2 mot spole 1. I spole 2 fins en lekkfluks ϕ_{lekk2} som ikke påvirker spole 1, samt fellesfluksen ϕ_m. i_1 og i_2 er strømmene i henholdsvis spole 1 og 2, og N_1 og N_2 er de respektive vindingstallene.



Figur 1.9: Fluksmønster for koblede spoler

Spolefluksen for de to spolene er gitt ved

$$\begin{aligned} \psi_1 &= \psi_{\text{lekk1}} + \psi_m = L_{\text{lekk1}} i_1 + M i_2 \\ \psi_2 &= \psi_{\text{lekk2}} + \psi_m = M i_1 + L_{\text{lekk2}} i_2 \end{aligned} \tag{1.13}$$

hvor M er den gjensidige induktansen mellom spolene. Av formel (1.13) fremgår at fluksen i en av spolene blir påvirket av strømmene i begge. Spolene er koblet.

Faradays lov fastslår at en fluksendring i en spole skaper en indusert spenning. På bakgrunn av det som tidligere er nevnt, kan den uttrykkes på ulike måter, som vist i formel (1.14):

$$e = N\frac{d\phi}{dt} = L\frac{di}{dt} = \frac{d\psi}{dt} \tag{1.14}$$

Dersom fluksendringene følger en sinusform, finner vi følgende sammenheng mellom effektivverdiene av indusert spenning og spolefluks:

$$E = k \cdot \Psi$$

Dersom den gjensidige induktansen M skulle være forsvinnende liten, betyr det at spolene er frittstående, og bare egeninduktansen L_1 og L_2 er tilbake. Spolene befinner seg så langt fra hverandre at magnetfeltene ikke vekselvirker. Skulle derimot spolene være plassert på en felles kjerne, vil den gjensidige induktansen M være mye større enn lekkinduktansene L_{lekk1} og L_{lekk2}. Spolene er da sterkt koblet, og spolestrømmene vil i høy grad påvirke hverandre. Denne kretsen kalles en transformator.

1.7 Øvingsoppgaver

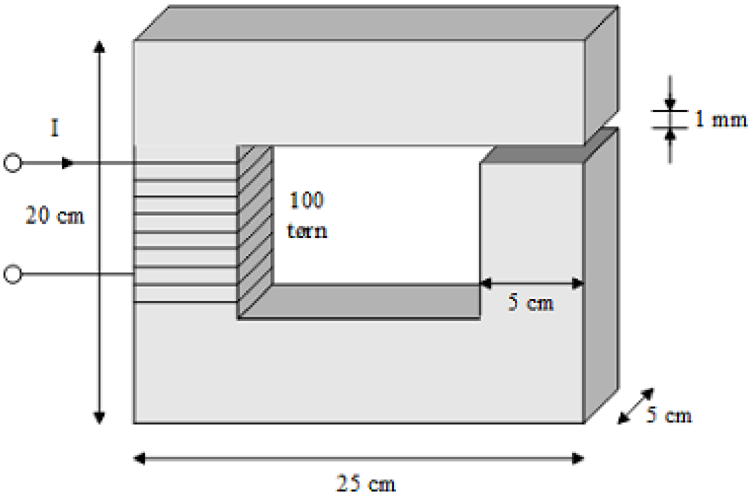
1. En spole med jernkjerne og luftgap er vist på figur 1.10. Sett opp en ekvivalent magnetisk krets. I et gitt tilfelle har kjernen en relativ permeabilitet $\mu_r = 850$. Beregn fluksen og flukstettheten i kjerna ved en strøm $I = 5,0\,\mathrm{A}$. Hvor høy feltstyrke er det i luftgapet? Hvor høy feltstyrke er det i jernkjerna?

2. I en spole med 500 tørn skjer det i et øyeblikk en fluksendring på $0,3\,\mathrm{Wb/\,s}$. Hvor høy spenning induseres i spolen?

3. Spolen som er nevnt i oppgave 2 har en induktans på $10\,\mathrm{mH}$. Hvor høy spenning induseres hvis det skjer en endring i spolestrømmen på $200\,\mathrm{A/\,s}$?

4. Hva er hysterese?

5. Hvorfor vekselvirker to spoler dersom de er plassert i nærheten av hverandre eller på felles kjerne?

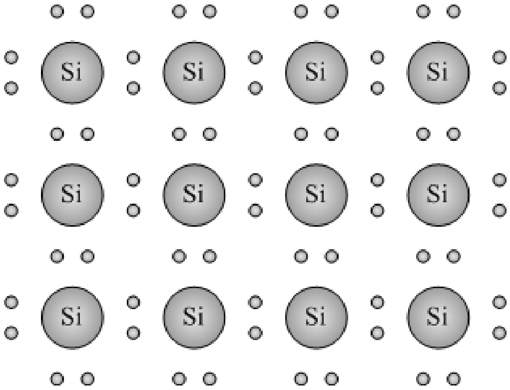


Figur 1.10: Spole med kjerne og luftgap

2 Grunnleggende halvlederteknikk

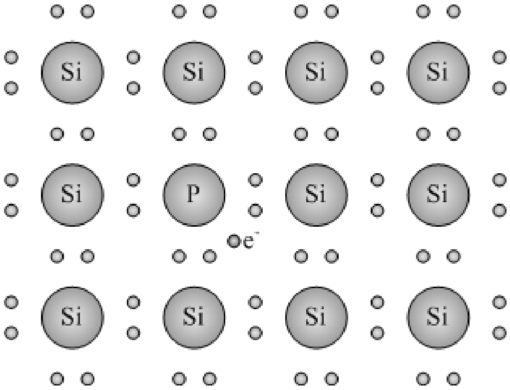
2.1 p- og n-materialer

Silisium er et grunnstoff med fire elektroner i ytterste skall. I ren form danner det en krystallstruktur som er vist forenklet på figur 2.1. Elektronene danner kovalente bindinger, og det er få frie ladningsbærere. Rent silisium er med andre ord en dårlig leder, men materialet er heller ikke en isolator. Materialet er en halvleder.



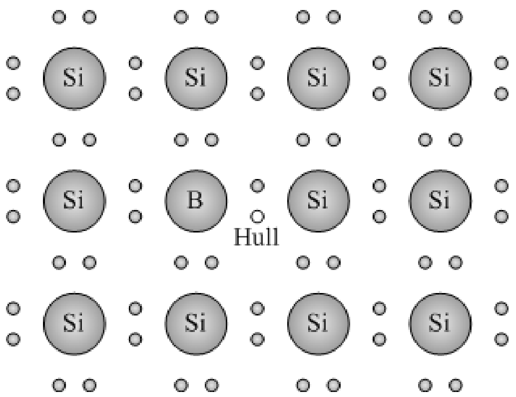
Figur 2.1: Forenklet krystallstruktur i rent silisium

Dersom man tilsetter små mengder fosfor, vil disse atomene finne plass i krystallgitteret, fordi de har omtrent samme størrelse som silisiumatomene. Siden fosfor har fem valenselektroner, vil ett av elektronene ikke finne plass i krystallgitteret og kan vandre fritt rundt i krystallet, slik det er vist på figur 2.2. Siden det er et overskudd av negative ladningsbærere, kalles materialet et n-materiale.

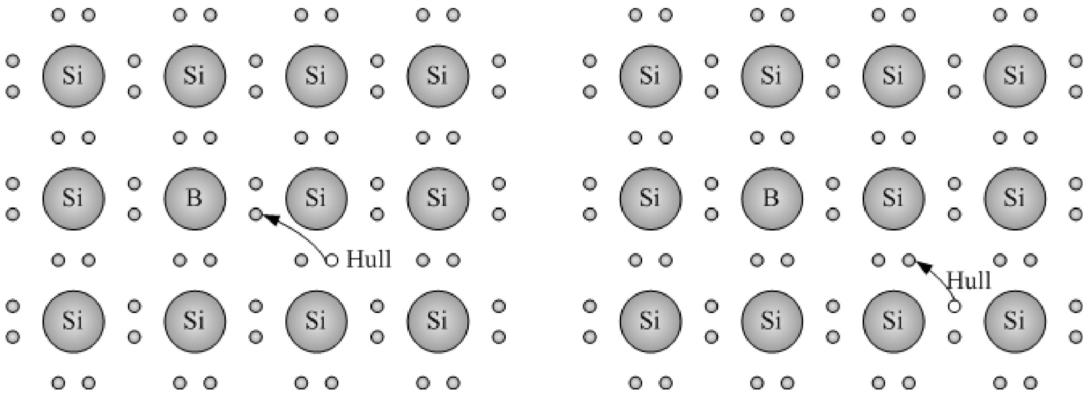


Figur 2.2: Silisiumkrystall dopet med fosfor (n-materiale)

Hvis man i stedet tilsetter bor, vil atomer med tre valenselektroner finne plass i krystallgitteret, som vist på figur 2.3. Boratomet vil danne et positivt ion (et hull). Hvis dette atomet ”stjeler” et elektron fra naboatomet, vil dette danne et hull, og slik kan hullet hoppe fra atom til atom, slik figur 2.4 viser. Hullene er positive ladningsbærere, og materialet kalles et p-materiale.



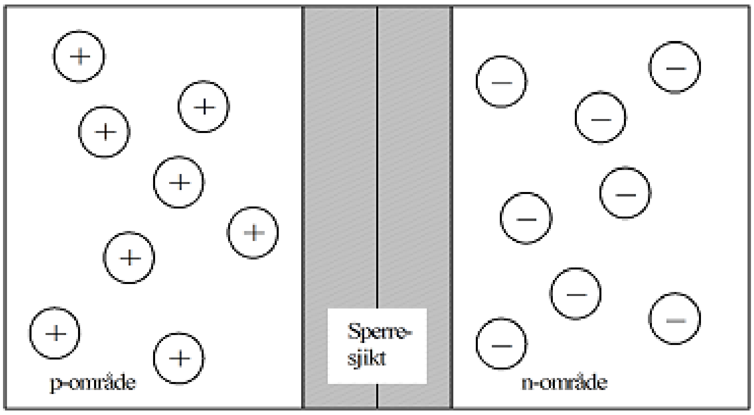
Figur 2.3: Silisiumkrystall dopet med bor (p-materiale)



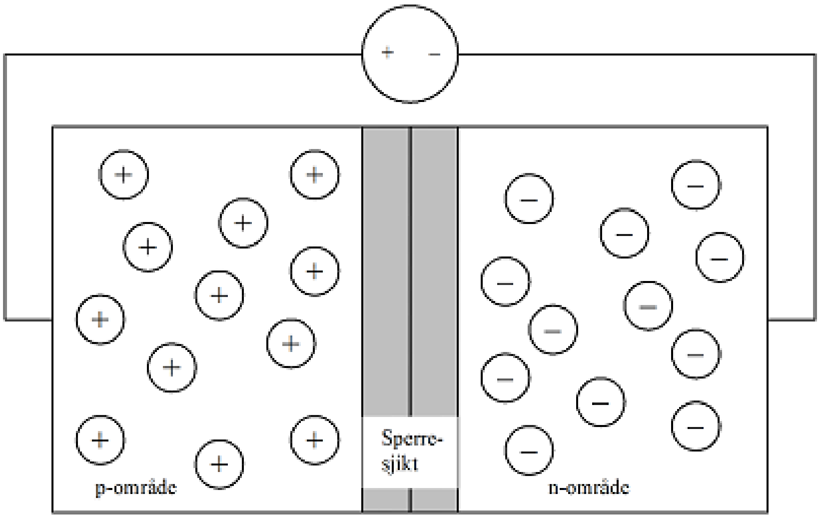
Figur 2.4: Forflytning av hull i p-materiale

2.2 Sperresjikt

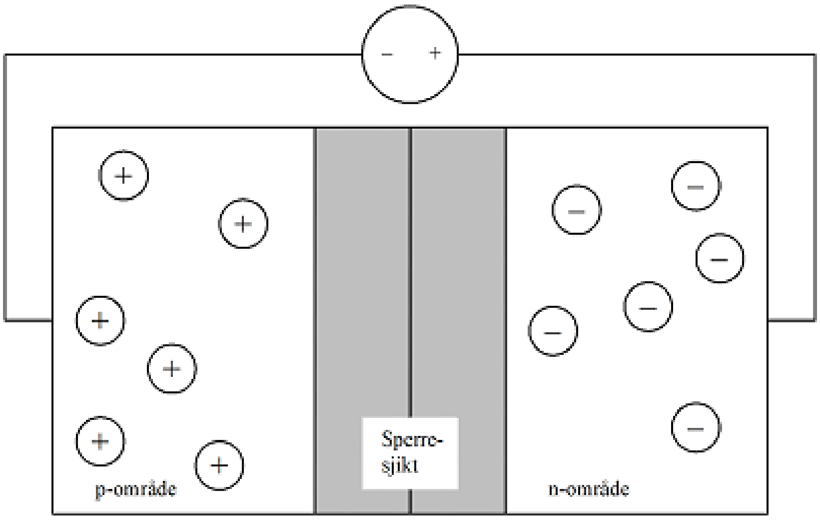
Setter man sammen et p- og et n-område i samme silisiumkrystall, vil nærliggende elektroner og hull rekombinere (slå seg sammen), og området rundt overgangssonen vil bestå av nøytrale atomer med få frie ladningsbærere. Dette området kalles et sperresjikt og er vist på figur 2.5.
Dersom man kobler en spenningskilde til krystallet med plusspolen tilkoblet p-området og minuspolen tilkoblet n-området, vil man erstatte noen av de ladningsbærerne som rekombinerte, og sperresjiktet blir smalere, som vist på figur 2.6.
Snur man derimot polariteten på spenningskilden, vil derimot enda flere frie ladningsbærere rekombinere, og sperresjiktet vokser, som vist på figur 2.7.



Figur 2.5: pn-overgang i silisiumkrystall med sperresjikt



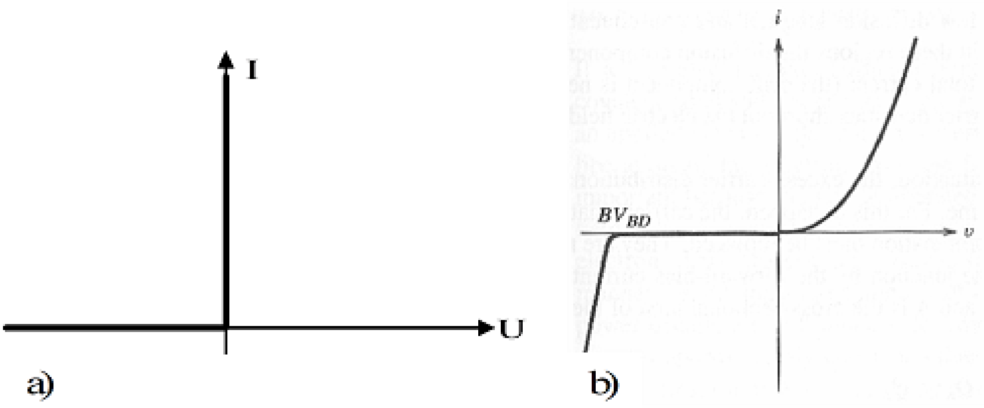
Figur 2.6: pn-overgang med påtrykt spenning i foroverretning



Figur 2.7: pn-overgang med påtrykt spenning i reversretning

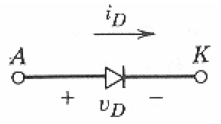
2.3 Diodens virkemåte

Dersom spenningen i foroverretning blir høy nok ($0,7$ V for silisiumkrystaller), forsvinner sperresjiktet helt, og kretsen leder strøm. pn-overgangen leder altså strøm i en retning og sperrer i motsatt retning. Dette er prinsippet for en diode, som er den mest brukte likeretterkomponenten.
En ideell diode vil ha en strøm/spenningskarakteristikk som vist på figur 2.8a og vil sperre fullstendig for spenninger i reversretning og vil lede for enhver spenning i foroverretning.



Figur 2.8: Diodekarakteristikk: a) Ideell diode, b) praktisk diode

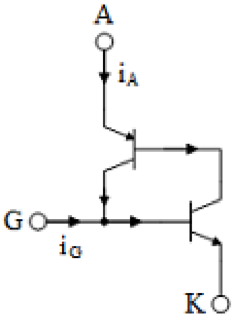
En praktisk diode vil ikke ha en slik ideell karakteristikk. For det første kreves det som før nevnt en viss positiv spenning for å bryte ned sperresjiktet. Dessuten vil materialet ha ohmske tap. På grunn av såkalte minoritetsbærere (elektroner i p-sjiktet og hull i n-sjiktet) vil dioden slippe gjennom en svak strøm i reversretning, og dersom den negative spenningen blir høy nok (zener-spenningen), bryter krystallstrukturen sammen, og dioden leder i reversretning. Karakteristikken for en praktisk diode er vist på figur 2.8b. Symbolet er vist på figur 2.9. Polariteten angir spenning i foroverretning, hvor A står for anode og K for katode. Dioden har ingen styreelektrode; det er kun retningen og størrelsen på påtrykt spenning som avgjør hvorvidt den leder eller ikke. Dioden er en svært mye brukt komponent, og innenfor kraftelektronikk brukes den til nettførte likerettere.



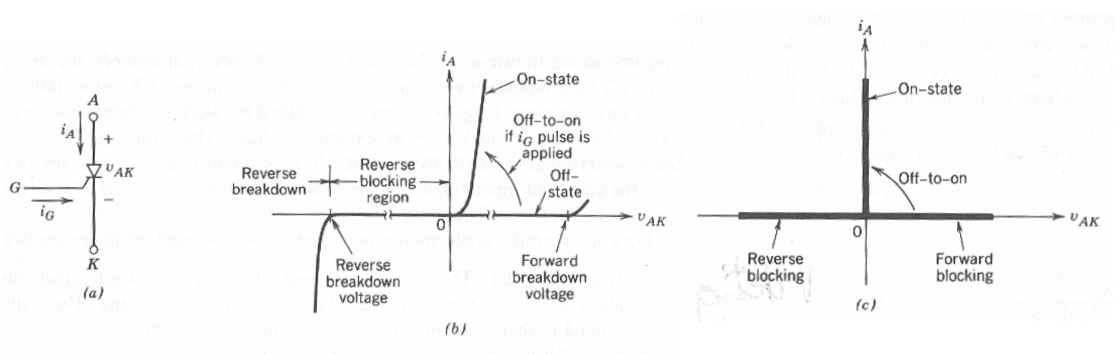
Figur 2.9: Symbol for diode

2.4 Tyristorer

Tyristoren er vist på figur 2.11 og har mye til felles med dioden, men den har en ekstra styreelektrode, gate, merket G på figur 2.11a. Prinsippet er vist på figur 2.10. En positiv strømpuls på den nederste transistoren gjør at den begynner å lede. Dette senker basis på den øverste PNP-transistoren som dermed også vil lede. Tyristoren fungerer som en holdekrets som fortsetter å lede til den blir strømløs.
Figur 2.11b og 2.11c viser henholdsvis praktisk og ideell karakteristikk. I likhet med dioden vil den sperre i reversretning. I foroverretning vil den også sperre helt til det kommer en tennpuls inn mellom gate og katode. Deretter vil den lede helt til strømmen slutter å flyte gjennom den. Tyristoren kan betraktes som en styrt diode og brukes mye til styrte (selvførte) strømrettere. Den er robust og tåler høye strømmer og spenninger.
Gate-turn-off tyristoren (GTO) kan i motsetning til den vanlige tyristoren slås av mens den leder. Dette gjøres ved å sende en negativ strømpuls inn mellom gate og katode. På figur 2.10 kan dette forklares

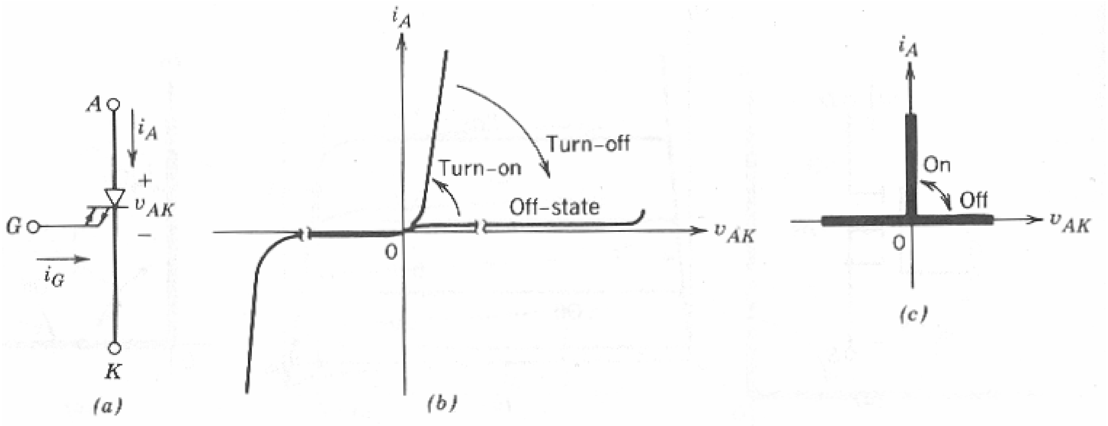


Figur 2.10: Prinsipiell oppbygging av tyristor



Figur 2.11: Tyristorens symbol og karakteristikk

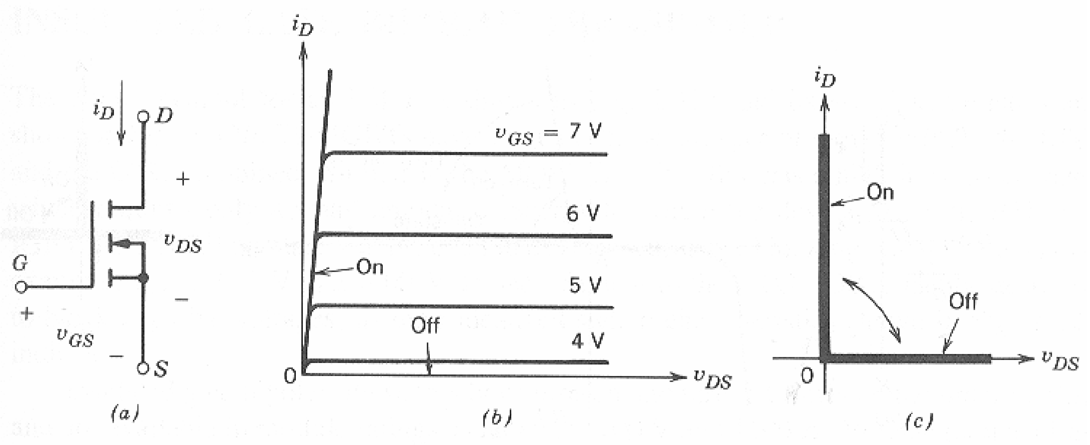
med at den negative strømpulsen på gate oppveier den positive grenstrømmen som flyter inn på basis til den nedre transistoren. Denne sperrer, og da slukkes holdekretsen. Figur 2.12 viser skjemasymbol og karakteristikk. Når strømmen i kretsen brytes på denne måten, vil induktanser i kretsen skape store spenningssprang. Derfor brukes ofte en snubber-krets (støtdemper) for å dempe spenningsspranget noe når tyristoren slås av. En GTO tåler store strømmer og spenninger, i likhet med en vanlig tyristor.



Figur 2.12: Symbol og karakteristikk for en GTO

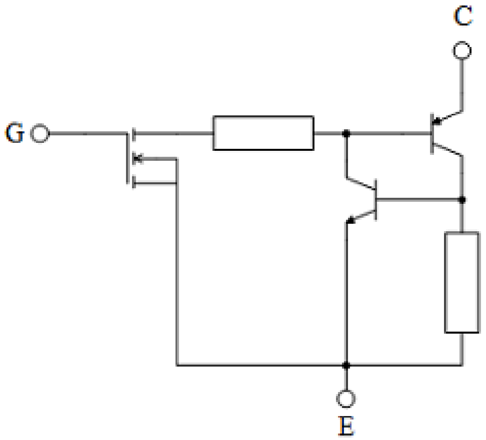
2.5 Transistorer

Metal-oxide-semiconductor field effect transistor (MOSFET) er en felteffekttransistor hvor styreelektroden (gate) er isolert fra silisiumkrystallet av et tynt metalloksid-sjikt. Symbol og karakteristikk er vist på figur 2.13. Elektrodene kalles source (S), gate (G) og drain (D). Dersom det ikke er noen spenning på inngangen mellom gate og source, vil transistoren sperre mellom drain og source. Dersom det påtrykkes en positiv spenning, som vist på figur 2.13b, vil transistoren lede, og fjernes denne inngangsspenningen, vil den sperre igjen. Transistoren tåler ikke svært høye strømmer og spenninger, men åpner og lukker meget hurtig.



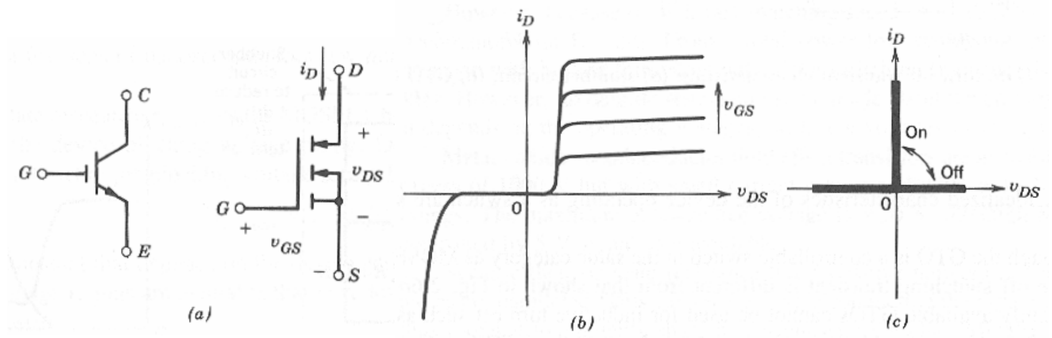
Figur 2.13: Symbol og karakteristikk for en MOSFET

Insulated gate bipolar transistor (IGBT) er en mellomting mellom en MOSFET og en tradisjonell bipolar transistor. Dette fremkommer av figur MOSFET-transistoren på inngangen fungerer som en driverkrets for en holdekobling som består av to bipolare transistorer.



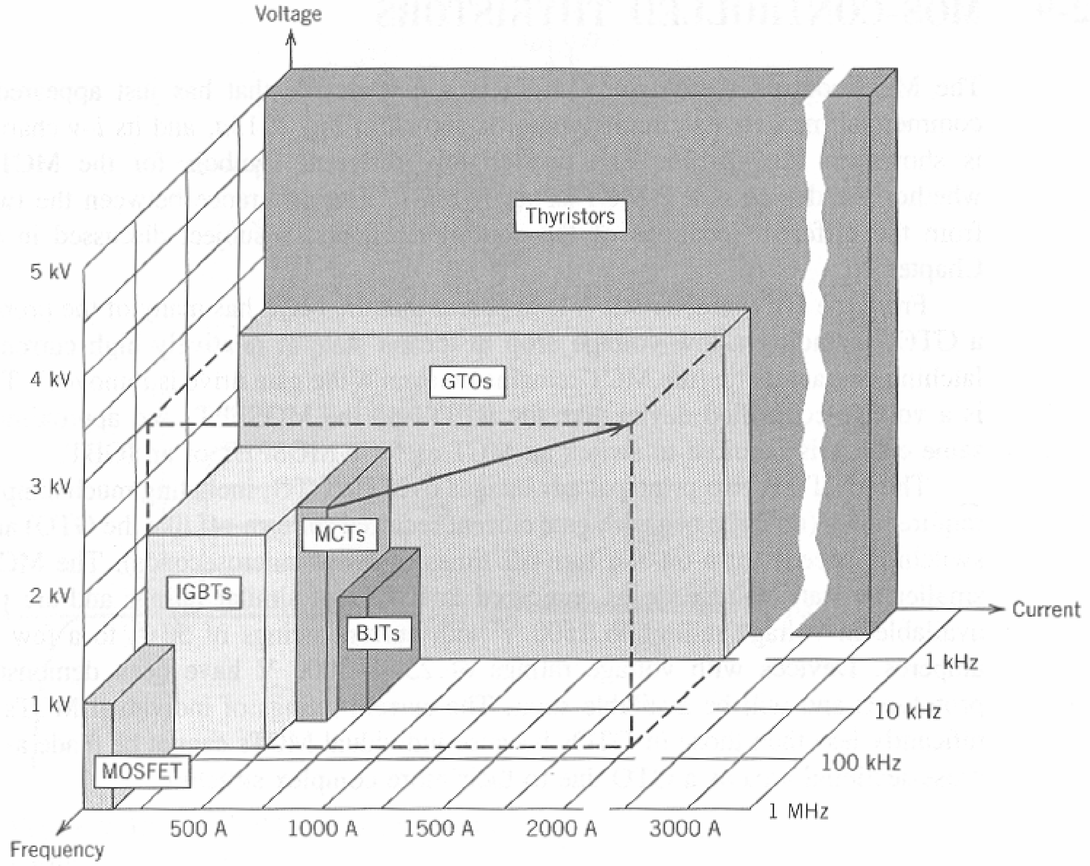
Figur 2.14: Prinsipiell oppbygging av IGBT

Derfor finnes det to ulike skjemasymboler, som vist på figur 2.15a. Det ene minner om symbolet for en vanlig transistor og kaller elektrodene for emitter (E), gate (G) og kollektor (C). Det andre er nesten identisk med symbolet for en MOSFET og bruker samme betgnelse på elektrodene. Den tåler noe mer strøm og spenning enn en MOSFET, men er noe langsommere.



Figur 2.15: Symbol og karakteristikk for en IGBT

Figur 2.16 sammenligner de ulike halvlederkomponentene. Det fremgår av figuren at den tradisjonelle tyristoren er den desidert mest robuste av disse komponentene, men også den langsomste. I andre enden av skalaen befinner MOSFET-transistoren seg. Denne tåler ikke store effekter, men er ekstremt rask.
Ved bygging av høyspent fasekompenseringsutstyr eller terminaler for overføring av høyspent likestrøm (HVDC), vil det være naturlig å bruke tyristorer, mens det i aktive strømrettere med høy svitsjefrekvens vil være naturlig å bruke MOSFET eller IGBT.

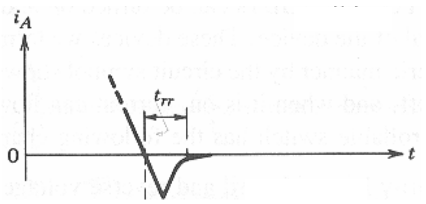


Figur 2.16: Sammenligning av ulike halvlederkomponenter

2.6 Gjenoppretting av sperresjikt

Under kapittel 2.2 lærte vi at sperresjiktet forsvinner når det påtrykkes en viss positiv spenning over dioden (eller tyristoren). For at dette sperresjiktet skal gjenopprettes, må det påtrykkes en negativ spenning av en viss størrelse og varighet, slik at de tilførte ladningene kan nøytralisere ladningsbærerne nærmest pn-overgangen.

For dioden har dette fenomenet ingen praktisk betydning; den vil lede i en retning og sperre i motsatt retning. For tyristoren har gjenopprettingen av sperresjiktet stor betydning. Etter at den har ledet og er gjort strømløs, må sperresjiktet gjenopprettes. Hvis ikke, vil den ikke sperre i foroverretning, men virke som en vanlig diode. Figur 2.17 viser denne negative strømmen som må til for å gjenopprette sperresjiktet og som krever en viss tid t_{rr} (rr står for reverse recovery).



Figur 2.17: Gjenoppretting av sperresjikt i tyristor

2.7 Tap

Kraftelektronikkomponenter kalles svitsjer (brytere eller ventiler) fordi de opereres i to tilstander: av eller på. Når de er av, flyter det ingen strøm i komponenten, og det er følgelig heller ingen tap. Når de er på, vil det være visse ohmske tap på grunn av komponentens indre resistans. Disse tapene kalles statiske tap.

Akkurat idet svitsjene slås på eller av, vil det være en overgangstilstand hvor resistansen er relativt høy og det er et visst spenningsfall over komponenten. Disse tapene kalles dynamiske tap og vil være avhengig av hvor raskt svitsjingen skjer, og hvor ofte. Figur 2.18 illustrerer statiske og dynamiske tap i en halvlederkomponent. Siden tapsenergi tilsvarer effekt multiplisert med tid, vil tapsvarmen tilsvare det skraverte arealet under effektkurven nederst på figur 2.18. Det fremgår av figuren at de dynamiske tapene er betydelig større enn de statiske. Jo raskere svitsjefrekvens en velger, jo tettere vil ”pyramidene” på figur 2.18 komme, og jo større varmetap vil en få. Dette er grunnen til at en kan få problemer med varmgang i datamaskiner dersom en velger å øke klokkefrekvensen for å gjøre maskinen raskere. Også i aktive strømrettere må en ta hensyn til dynamiske tap og sørge for tilstrekkelig kjøling, dersom en velger å bruke en høy svitsjefrekvens. Tapseffekten er gitt ved

$$\Delta P = \frac{W_{statisk} + W_{dynamisk}}{T} \tag{2.1}$$

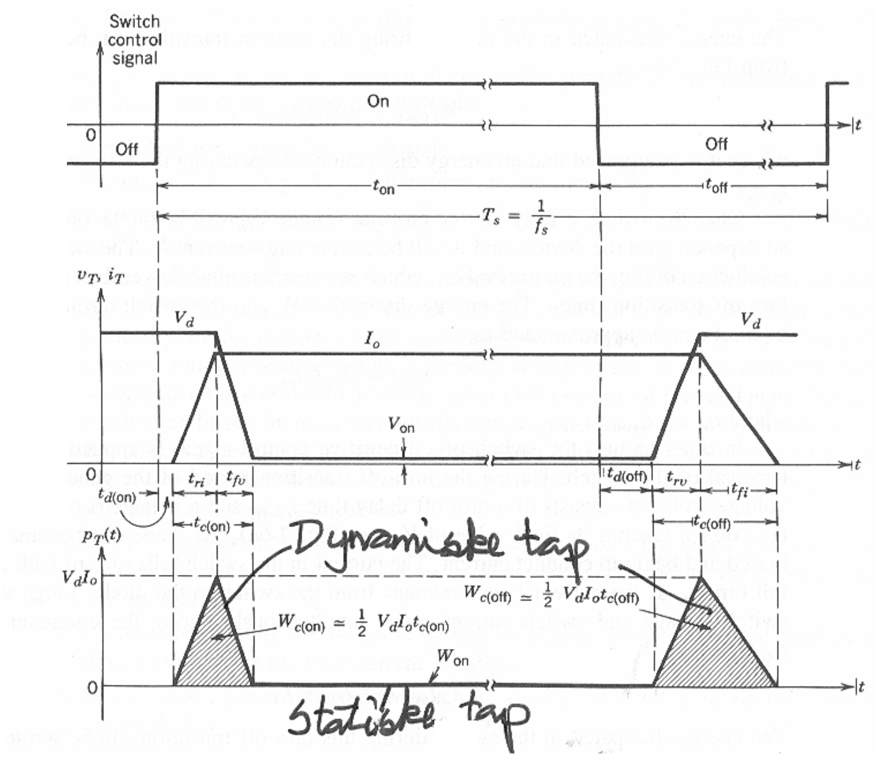
hvor ΔP er tapseffekten, $W_{statisk}$ er statiske tap, $W_{dynamisk}$ er dynamiske tap, og T er svitsjeperioden.

Eksempel 1 *En halvlederkomponent har statiske og dynamiske tap som vist på figur 2.19. Beregn tapseffekten. Hvor høy blir tapseffekten hvis svitsjefrekvensen endres til* $33\,\mathrm{kHz}$*?*

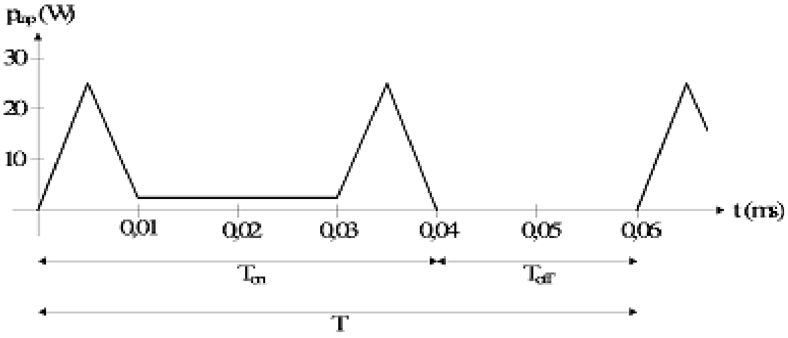
Løsning:

Varmeutviklingen ved de statiske tapene utgjør arealet av et rektangel med høyde $2,5\,\mathrm{W}$ og bredde $20\,\mu\mathrm{s}$:

$$W_{statisk} = 2,5 \cdot 20 \cdot 10^{-6} = 50\,\mu\mathrm{J}$$



Figur 2.18: Svitjsetap i en halvlederkomponent. Øverst: kontrollsignal, i midten: strøm og spenning, nederst: tapseffekt



Figur 2.19: Statiske og dynamiske tap

Varmeutviklingen ved de dynamiske tapene utgjør arealet av to triangler med høyde $25\,\mathrm{W}$ og bredde $10\,\mu\mathrm{s}$:

$$W_{dynamisk} = 2 \cdot \frac{25 \cdot 10 \cdot 10^{-6}}{2} = 25 \cdot 10 \cdot 10^{-6} = 250\,\mu\mathrm{J}$$

Tapseffekten er lik summen av tapsvarmen delt på periodetiden:

$$\Delta P = \frac{W_{statisk} + W_{dynamisk}}{T} = \frac{(50 + 250)\ \mu\mathrm{J}}{60\,\mu\mathrm{s}} = 5,0\,\mathrm{W}$$

Ved en frekvens på $33\,\mathrm{kHz}$ blir periodetiden:

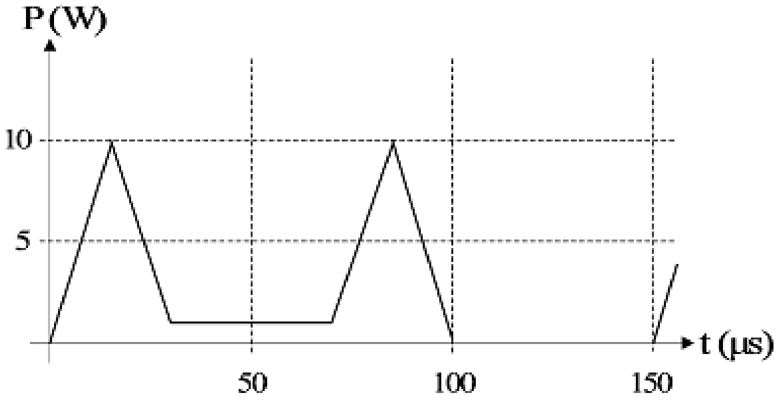
$$T = \frac{1}{f} = \frac{1}{33000} \approx 30\,\mu\mathrm{s}$$

Da vil “pyramidene” bli klemt sammen, slik at de dynamiske tapene dominerer fullstendig, og de statiske er neglisjerbare:

$$\Delta P = \frac{250\,\mu\mathrm{J}}{30\,\mu\mathrm{s}} = 8,33\,\mathrm{W}$$

2.8 Øvingsoppgaver

1. Hva er et p-sjikt, og hva er et n-sjikt?
2. Forklar hvorfor det oppstår et sperresjikt rundt en såkalt pn-overgang.
3. Hva er den grunnleggende forskjellen mellom en diode og en tyristor? Hvilken tilleggsfunksjonalitet har en GTO?
4. Hvilke fordeler har en transistor sammenlignet med en tyristor, og hvilke ulemper har den?
5. Hva er statiske, og hva er dynamiske tap?
6. Figur 2.20 viser øyeblikksverdien av tapene i en svitsj. Beregn tapseffekten.

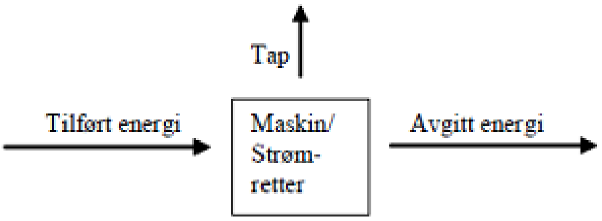


Figur 2.20: Svitsjetap

3 Termiske forhold. Merking og kapsling

3.1 Energiomforming

Alle typer elektriske maskiner og strømrettere tilføres energi og avgir energi. En del av den tilførte energien omdannes til tap og skaper varmeutvikling. Figur 3.1 viser sammenhengen mellom tilført energi, avgitt energi og tap.



Ut fra disse forholdene kan man formulere en generell energiligning for denne type utstyr:

$$W_{el} + W_{mek} = W_{varme} + W_{magn} + W_{kin} \tag{3.1}$$

hvor mekanisk og kinetisk energi naturligvis ikke vil være representert for en transformator eller en strømretter. Uttrykkene til venstre i ligningen utgjør tilført og avgitt energi, mens uttrykkene til høyre utgjør magasinert energi og tapsenergi (varme).

3.2 Varmeutvikling og kjøling

I kapittel 5 beskrives transformatorens samlede tap ΔP, som er differansen mellom tilført og avgitt aktiv effekt:

$$\begin{gathered} \Delta P = P_1 - P_2 \\ \Delta P = P_0 + P_b \\ P_0 = P_{hy} + P_{vi} \\ P_b = P_{DC} + P_{till} \end{gathered} \tag{3.2}$$

hvor P_{hy} representerer hysteresetap og P_{vi} virvelstrømstap. P_{DC} utgjør strømvarmetap ved likestrøm, og P_{till} er tilleggstapene forårsaket av vekselstrøm.
For en roterende elektrisk maskin vil en i tillegg ha et friksjonstap P_{fr} som skyldes friksjon i lager, luft og eventuelle børster. Da vil tomgangstapet skrives som

$$P_0 = P_{hy} + P_{vi} + P_{fr} \tag{3.3}$$

I en strømretter vil det ikke være noen nevneverdige tomgangstap, og belastningstapene utgjøres av de totale svitsjetapene:

$$P_b = P_{sw} \tag{3.4}$$

hvor de dynamiske svitsjetapene som regel er mye større enn de statiske.
Felles for alle systemene er at belastningstapene har sitt opphav i resistanser (strømvarmetap) og er proporsjonale med kvadratet av belastningsstrømmen:

$$P_b = \Sigma R I^2 \tag{3.5}$$

Tapene i elektriske ledere og magnetisk materiale skaper en varmeutvikling i jernkjerne, viklinger, tilførselsledninger og silisiumkrystaller. Varmen transporteres bort via kjølesystemer og ut til omgivelsene. Resultatet er at temperaturen faller jo lenger unna varmekildene en kommer, og omgivelsestemperaturen vil alltid være lavere enn maskintemperaturen. Temperaturen vil altså være lavere i transformatoroljen enn i viklingene, og lavere på utsiden av transformatorkassen enn i oljen. Temperaturen vil være høyere inne i en transistor enn utenpå, og høyere utenpå transistorene enn utenpå kjøleribben. Forskjellen mellom maskintemperatur og omgivelsestemperatur kalles overtemperatur med θ som symbol, mens absolutte temperaturer angis med ϑ:

$$\theta = \vartheta_{maskin} - \vartheta_{omg} \tag{3.6}$$

I videre temperaturbetraktninger gjøres følgende forenklinger:

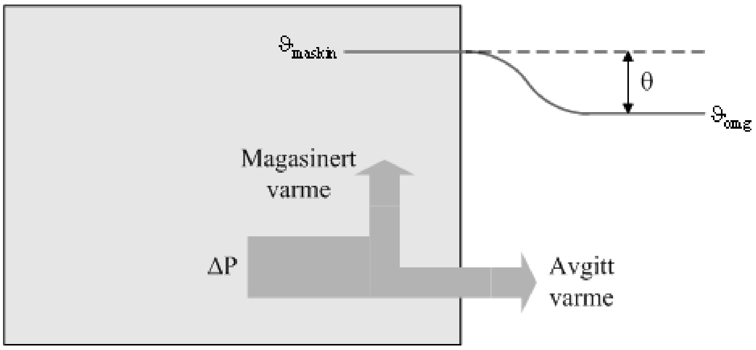
- Omgivelsestemperaturen regnes som stabil.
- Tapene, og dermed varmeproduksjonen, regnes som konstant
- Det er samme temperatur overalt i maskinen eller strømretteren

Sammenhengen mellom maskinens tap ΔP og overtemperaturen θ er gitt ved

$$\Delta P = c \cdot m \frac{d\theta}{dt} + \alpha \cdot A \cdot \theta \tag{3.7}$$

hvor
c er spesifikk varmekapasitet
m er maskinmassen
α er varmeovergangstallet
A er varmeavgivende flate.

Leddet $c \cdot m \frac{d\theta}{dt}$ er magasinert varme i maskinmassen, og leddet $\alpha \cdot A \cdot \theta$ er avgitt varme til omgivelsene. Figur 3.1 illustrerer dette. Noe av tapseffekten magasineres, og noe strømmer ut til omgivelsene. Denne varmestrømmen henger sammen med et temperaturfall etter hvert som varmen spres og ledes bort.



Figur 3.1: Varmeflyt fra en maskin til omgivelsene

For en maskin som er kald ved oppstart, vil overtemperaturen endre seg på følgende måte over tid:

$$\theta = \theta_{\max} \left(1 - e^{-\frac{t}{T}}\right) \tag{3.8}$$

hvor $\theta_{\max}$ er maksimal overtemperatur, det vil si overtemperaturen etter lang tids drift, og $T = \frac{c \cdot m}{\alpha \cdot A}$ er maskinens termiske tidskonstant.
Formel (3.8) kan også skrives om slik at den gir et uttrykk for maskintemperaturen:

$$\vartheta_{mask} = (\vartheta_{slutt} - \vartheta_{omg}) \left(1 - e^{-\frac{t}{T}}\right) + \vartheta_{omg} \tag{3.9}$$

hvor ϑ_{slutt} er maskintemperaturen etter lang tids drift.

Etter lang tid vil maskintemperaturen, og dermed også overtemperaturen forbli konstant, og dermed vil leddet $\frac{d\theta}{dt} = 0$. Sammenhengen mellom tap og endelig overtemperatur er altså

$$\begin{gathered} \Delta P = \alpha \cdot A \cdot \theta_{slutt} \\ \Delta P = k \cdot \theta_{slutt} \end{gathered} \tag{3.10}$$

Som før nevnt, kan tapene deles inn i tomgangs- og belastningstap:

$$\Delta P = P_0 + P_b \tag{3.11}$$

Tomgangstapene er uavhengige av belastningen, mens belastningstapene endrer seg med kvadratet av laststrømmen:

$$P_b = \sum RI^2 \tag{3.12}$$

Siden endelig overtemperatur og tap er proporsjonale, kan også overtemperaturen deles inn i en tomgangs- og en belastningskomponent:

$$\theta_{slutt} = \theta_0 + \theta_b \tag{3.13}$$

hvor θ_0 er konstant, mens θ_b endrer seg med belastningen i kvadrat.

Eksempel 1 *a. En maskin befinner seg i et rom med en temperatur på* $20\,^\circ\mathrm{C}$*. I tomgang har maskinen en temperatur på* $35\,^\circ\mathrm{C}$*. Ved full last er maskintemperaturen* $85\,^\circ\mathrm{C}$ *etter lang tids drift. Hva blir den endelige maskintemperaturen ved en lastøkning på* 20%*?*

b. Maskinen har en termisk tidskonstant $T = 10\,\mathrm{min}$*. Hva er maskintemperaturen etter* $25\,\mathrm{min}$ *når maskinen går kontinuerlig med full last etter å ha vært avkjølt til omgivelsestemperatur?*

Løsning:

a.

Overtemperaturen θ_0 er

$$\theta_0 = \vartheta_{maskin,tomg} - \vartheta_{omg} = 35 - 20 = 15\,^\circ$$

Overtemperaturen ved full last er

$$\theta_{\max} = \vartheta_{maskin} - \vartheta_{omg} = 85 - 20 = 65\,^\circ$$

Den belastningsavhengige overtemperaturen er

$$\theta_{\,b,100\%} = \theta_{\max} - \theta_0 = 65 - 15 = 50\,^\circ$$

Ved 120% last blir denne overtemperaturen

$$\theta_{\,b,120\%} = 50 \cdot \left(\frac{120}{100}\right)^2 = 72\,^\circ$$

Maskintemperatur ved lang tids overlast blir

$$\vartheta_{maskin,120\%} = \vartheta_{omg} + \theta_0 + \theta_{\,b,120\%} = 20 + 15 + 72 = 107\,^\circ\mathrm{C}$$

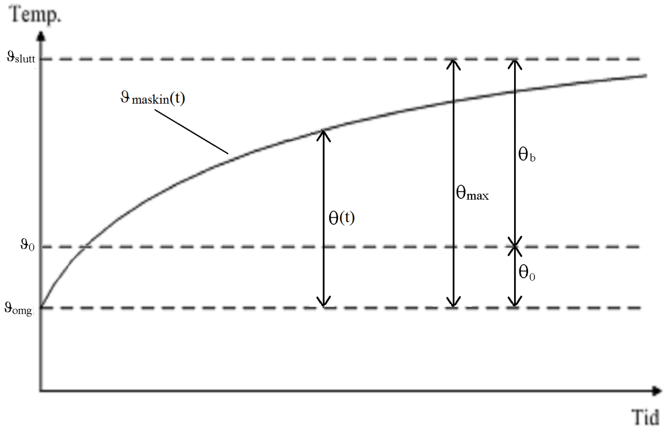
b.

Overtemperaturen som funksjon av tiden er gitt ved

$$\theta = \theta_{\max}\left(1 - e^{-\frac{t}{T}}\right)$$

Ved $25\,\mathrm{min}$ vil overtemperaturen være

$$\theta = 65 \cdot \left(1 - e^{-\frac{25}{10}}\right) \approx 60\,^\circ$$

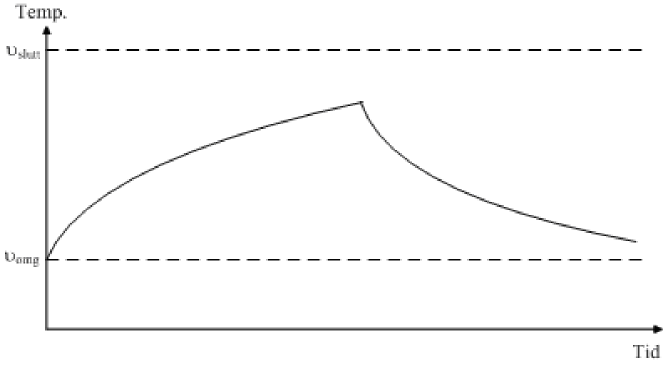


Figur 3.2: Maskintemperaturen ved kontinuerlig drift

Maskintemperaturen etter $25\,\mathrm{min}$ er

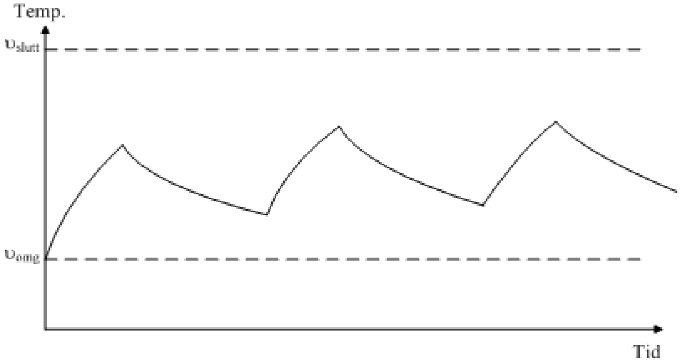
$$\vartheta_{maskin} = \vartheta_{omg} + \theta = 20 + 60 = 80\,^{\circ}\mathrm{C}$$

Figur 3.2 viser hvordan maskintemperaturen vil stige eksponensielt mot en konstant sluttemperatur ved kontinuerlig drift. Når en tid lik fem ganger maskinens termiske tidskonstant er medgått, har maskinen så å si nådd endelig sluttemperatur.
Dersom en slår av maskinen eller reduserer belastningen, vil maskintemperaturen synke. Figur 3.3 viser temperaturforløpet dersom maskinen slås helt av. Da vil den gradvis kjøles ned til omgivelsestemperaturen. Dersom den hadde kjørt med lett last, ville temperaturen ha sunket noe, men ikke like mye som på figuren. Denne driftsformen kalles korttidsdrift. Elektriske maskiner med lang termisk tidskonstant kan altså overbelastes i en kort periode, dersom de får anledning til å kjøle seg ned etterpå.



Figur 3.3: Maskintemperaturen ved korttidsdrift

En annen vanlig måte å operere en maskin på, er intermitterende drift, som er vist på figur 3.4. Da veksler maskinen mellom faste intervaller med tung last og utkobling eller lett last. Temperaturen vil da øke eller avta, avhengig av hvor stor belastningen er. Også i dette tilfellet kan maskinen overbelastes i korte perioder, bare den får kjølt seg tilstrekkelig ved lett last eller lastutkobling.
Ved intermitterende drift kan det være greit å kunne beregne hvor stor kontinuerlig effekt en maskin eller omformer må være merket for, slik at man unngår å velge en uforholdsmessig stor maskin og samtidig unngår overbelastning i tunglastperiodene. I de påfølgende utledningene for å finne et uttrykk for kontinuerlig lasteffekt er det gjort to forutsetninger: En ser bort fra tomgangstapene, og en antar at tunglastintervallene er så korte at maskinen ikke rekker å overopphetes.



Figur 3.4: Maskintemperaturen ved intermitterende drift

Sammenhengen mellom lasteffekt og laststrøm er som følger:

$$\begin{gathered} P_2 = U_2 \cdot I_2 \cdot \cos\varphi_2 \text{ (enfase)} \\ P_2 = \sqrt{3} \cdot U_2 \cdot I_2 \cdot \cos\varphi_2 \text{ (trefase)} \end{gathered} \tag{3.14}$$

Hvis effektfaktoren $\cos\varphi_2$ holdes uendret, vil lasteffekt og laststrøm dermed være proporsjonale størrelser. Sammenfatter en (3.12) og (3.14), finner en at belastningstapene er proporsjonale med kvadratet av lasteffekten:

$$P_b = k \cdot {P_2}^2 \tag{3.15}$$

Ved intermitterende drift ønsker en å beregne midlere belastningstap:

$$P_b = k \cdot \frac{t_1 {P_1}^2 + t_2 {P_2}^2 + ...}{T} \tag{3.16}$$

hvor P_1, P_2,... er lasteffekten i løpet av de ulike driftsintervallene, t_1, t_2,... er varigheten av de ulike intervallene og T er varigheten av hele den intermitterende syklusen. Siden kontinuerlig lasteffekt er proporsjonal med midlere belastningstap i kvadrat, kan en sette

$$P = \sqrt{\frac{t_1 {P_1}^2 + t_2 {P_2}^2 + ...}{T}} \tag{3.17}$$

Eksempel 2 *En maskin som arbeider i omgivelsestemperatur* $20\ ^\circ$*C har samlede tap på* 200 *W og stabil maskintemperatur på* $60\ ^\circ$*C. Hva blir stabil maskintemperatur hvis lasten økes slik at tapene økes til* 400 *W?*

Løsning:
Overtemperatur ved 200 W er

$$\theta_{200\,\mathrm{W}} = \vartheta_{slutt,200} - \vartheta_{omg} = 60 - 20 = 40\,^\circ$$

Siden overtemperaturen er proporsjonal med tapseffekten, vil overtemperaturen ved 400 W være

$$\theta_{400\,\mathrm{W}} = \theta_{200\,\mathrm{W}} \frac{400\,\mathrm{W}}{200\,\mathrm{W}} = 80\,^\circ$$

Stabil maskintemperatur bli da

$$\vartheta_{slutt,400} = \vartheta_{omg} + \theta_{400\,\mathrm{W}} = 20 + 80 = 100\,^\circ\mathrm{C}$$

Eksempel 3 *En forbrenningsprosess trekker* $100\,\mathrm{kW}$ *i* 5 *minutter,* $20\,\mathrm{kW}$ *i* 10 *minutter og kobler ut i* 15 *minutter. Det skal velges en transformator som forsyner denne prosessen, og maskinen har så lang termisk tidskonstant at en kan benytte (3.17) for å beregne hvor høy effekt maskinen må kunne klare. Velg* $\cos\varphi = 0,8$*, og beregn nødvendig maskinytelse.*

Løsning:
Kontinuerlig aktiv effekt blir

$$P = \sqrt{\frac{t_1 P_1{}^2 + t_2 P_2{}^2 + 0}{T}} = \sqrt{\frac{5 \cdot 100^2 + 10 \cdot 20^2 + 0}{5 + 10 + 15}} = 42,4\,\mathrm{kW}$$

Maskinen må minst være merket for

$$S = \frac{P}{\cos\varphi} = \frac{42,4}{0,8} = 53\,\mathrm{kV\,A}$$

3.3 Merking og kapsling

Hvor stor effekt en maskin eller strømretter kan overføre, vil være begrenset av termiske forhold, enten det gjelder viklingstemperatur, kjernetemperatur eller sjikttemperatur i halvledere. Når en maskin eller strømretter er merket for en gitt effekt, må en vite hvilken driftsform merkingen gjelder for.
For likestrømsgeneratorer skal den elektriske ytelse ved klemmene oppgis i W, kW eller MW.
For vekselstrømsgeneratorer skal den tilsynelatende elektriske ytelse ved klemmene oppgis i VA, kVA eller MVA.
For motorer skal den mekaniske ytelse på akselen oppgis i W, kW eller MW.
For motorer mindre enn 100W kan tilført elektrisk effekt oppgis i W eller VA.
For transformatorer skal den tilsynelatende elektriske ytelse ved klemmene oppgis i VA, kVA eller MVA.
For strømrettere brukes både aktiv og tilsynelatende effekt, avhengig av om de skal oppta/levere reaktiv effekt eller ikke, så de kan følgelig merkes med W, kW, MW eller VA, kVA, MVA.
For øvrig merkes elektriske maskiner med fabrikat og fabrikasjonsnummer. Strømarten (veksel- eller likestrøm) bør være oppgitt. Merkespenning(er) og frekvens (ved vekselstrøm) bør også stå på skiltet.

Tabell 3.1: Tillatte temperaturer for isolasjonsklasser

Isolasjonsklasse	A	E	B	F	H
Midl. vikl.temp (°C)	100	115	120	140	165
Maks. vikl.temp (°C)	105	120	130	155	180

Transformatorer merkes med koblingsgruppe og relative spenningsfall . Motorer merkes med turtall og effektfaktor.

Strømrettere merkes på ulike måter. Annen informasjon kan også være gitt på merkeskiltet for de ulike maskintypene.

Ulike isolasjonsklasser har ulik tillatt viklingstemperatur. Tabell 3.1 viser de ulike klassene.

Det stilles generelle krav til elektriske apparater som skal kunne tilkobles nettet, både elektriske maskiner og strømrettere. Apparatene må være utstyrt slik at de gir beskyttelse mot elektrisk støt, beskyttelse mot termiske virkninger, beskyttelse mot overstrøm, beskyttelse mot overspenning, beskyttelse mot underspenning, samt at frakobling og utkobling skal skje på en sikker måte, og det skal foreligge rutiner for iverksettelse av sikkerhetstiltak.

3.4 Aldring

Levetiden til en maskin eller omformer er i høy grad avhengig av omgivelsene den befinner seg i. Det er mange fysiske forhold som belaster en maskin: Temperatur, mekaniske påkjenninger, elektriske felt, forurensninger, fukt eller kondens.

Den viktigste faktoren av alle er temperaturen, og Montsingers lov tilsier at en temperaturøkning på åtte grader halverer isolasjonens levetid. Derfor er det viktig å holde viklingstemperaturen og kjernetemperaturen lavest mulig.

Alle elektriske maskiner utsettes for mekaniske påkjenninger, men den mekaniske slitasjen vil være mye større for en roterende maskin enn for en transformator. For høyspent utstyr må en dessuten ta hensyn til elektrisk feltstyrke. Over tid vil isolasjonsmaterialet forringes på grunn av dielektriske tap, ujevnheter og forurensninger i materialet.

Støv, urenheter og kondens er skadelig for alle typer elektriske maskiner. I transformatoroljen vil det trenge inn fukt, og oljen brytes ned til forurensningsprodukter. Dette reduserer isolasjonsevnen. I roterende maskiner kan fukt og forurensninger både bidra til økt slitasje, dårligere kjøling og overslag.

En maskin som er redusert på grunn av temperatur eller andre ugunstige forhold, vil ikke ”reparere” seg selv hvis man fjerner årsakene til aldringen, men man vil forlenge den gjenværende levetiden. Dette er verd å ta med i regnskapet når man finner det lønnsomt å kjøre en maskin over merkeeffekt i perioder. Den økte produksjonen kan fort bli spist opp av økte vedlikeholdskostnader.

3.5 Kapslingsgrad

IP-systemet (fra engelsk International Protection eller Ingress Protection) er et system for å angi kapslingsgraden til elektrisk utstyr, det vil si utstyrets beskyttelse mot inntrenging av faste gjenstander og vann. Det er en internasjonal standard definert i IEC 60529. Kapslingsgraden angis med bokstavene «IP» etterfulgt av to sifre (tabellene nedenfor viser sifrenes betydning).
Det første sifferet angir utstyrets beskyttelse mot inntrengning av faste gjenstander for eksempel støv, og utilsiktet kontakt med spenningsførende deler av kroppsdeler som for eksempel fingre.

Tabell 3.2: Første siffer

siffer	Beskyttelse av utstyret mot faste partikler	Beskyttelse av personer mot farlige deler
0	Ingen beskyttelse	Ingen beskyttelse
1	Større enn $50\,\mathrm{mm}$	Store kroppsdeler, for eksempel en håndflate
2	Større enn $12,5\,\mathrm{mm}$	Finger, $12,5\,\mathrm{mm}$ diameter
3	Større enn $2,5\,\mathrm{mm}$	Verktøy, $2,5\,\mathrm{mm}$ mm diameter
4	Større enn $1\,\mathrm{mm}$	Tråd, $1\,\mathrm{mm}$ diameter
5	Støvbeskyttet	Beskytter mot støv som kan skade produkt/innmat.
6	Støvtett	Komplett beskyttelse mot støvgjennomtrengning.

Det andre sifferet angir utstyrets beskyttelse mot skadelig vanninntrengning.

Tabell 3.3: Andre siffer

siffer	Beskyttelse mot vanninntrengning	Detaljer
0	Ingen beskyttelse	Ingen beskyttelse
1	Vertikale drypp	Vertikale drypp skal ikke ha skadelig virkning
2	Vertikale drypp ved helning opp til 15°	Vertikale drypp skal ikke ha skadelig virkning når utstyret har helningsvinkel opp til 15° i forhold til vertikallinjen
3	Dusj/regn	Dusj/regn mot kapsling i en vinkel opp til 60° i forhold til vertikallinjen skal ikke ha skadelig virkning
4	Sprut fra alle kanter	Sprut (kraftig dusj/regn) mot kapsling fra alle kanter skal ikke ha skadelig virkning
5	Spyling fra alle kanter	Spyling (fra slange/dyse) mot kapsling fra alle kanter skal ikke ha skadelig virkning
6	Kraftig spyling fra alle kanter	Kraftig spyling mot kapsling fra alle kanter skal ikke ha skadelig virkning
7	Kortvarig neddykking i vann	Ingen skadelig virkning ved kortvarig neddykking i vann (15 til $100\,\mathrm{cm}$ i inntil 30 minutter)
8	Varig neddykking	Ingen skadelig virkning ved varig neddykking i vann under betingelser spesifisert gjennom avtale mellom kunde og produsent av utstyret

3.6 Øvingsoppgaver

1. Hvilken energiform utvikles som følge av tapene i en maskin eller omformer?
2. Hva ligger i begrepet overtemperatur?
3. En maskin veier 4 tonn, har en overflate på $6\,\mathrm{m}^2$, en spesifikk varmekapasitet på $400\,\mathrm{J}/\,\mathrm{kg}\cdot\,\mathrm{K}$ og et varmeovergangstall (U-verdi) på $220\,\mathrm{W}/\,\mathrm{m}^2\cdot\mathrm{K}$. Beregn maskinens termiske tidskonstant.
4. Maskinen i oppgave 3 står i et rom med en omgivelsestemperatur på $15\,°\mathrm{C}$. Etter lang tids kontinuerlig drift med merkeeffekt når maskinen en temperatur på $75\,°\mathrm{C}$. Tomgangstapet er på $20\,\mathrm{kW}$ og belastningstapet $60\,\mathrm{kW}$. Hva er maskintemperaturen etter 15 minutter dersom maskinen er kald når den starter opp?
5. Hva blir sluttemperaturen dersom maskinen i oppgave 3 og 4 går med 75% av merkelast i en lang periode?
6. En maskin i intermitterende drift belastes med $50\,\mathrm{kW}$ i 10 minutter, med $20\,\mathrm{kW}$ i 10 minutter og står ubelastet i 10 minutter. Hvilken kontinuerlig effekt må maskinen være merket for?
7. En transformator har en beregnet levetid på 30 år ved en driftstemperatur på $75\,°\mathrm{C}$. Hva blir omtrentlig levetid hvis driftstemperaturen økes til $83\,°\mathrm{C}$?

4 Lysdimmere

Middelverdi og effektivverdi

Det er to definisjoner som er viktige å ha klart for seg når en skal analysere størrelsen av strømmer og spenninger i kraftelektronikkretser.

Middelverdien av en størrelse gis ved å integrere øyeblikksverdiene over en hel periode, og deretter dele resultatet med periodetiden. Dette er vist i formel (4.1):

$$\begin{aligned} U_{mid} &= \tfrac{1}{2\pi}\int\limits_0^{2\pi} u\cdot d\omega t \\ I_{mid} &= \tfrac{1}{2\pi}\int\limits_0^{2\pi} i\cdot d\omega t \end{aligned} \tag{4.1}$$

Middelverdien måles med et dreiespoleinstrument.

Effektivverdien (Root mean squared – RMS) gis ved å kvadrere størrelsen, beregne middelverdien som ved formel (4.1), og deretter beregne kvadratroten av uttrykket. Formel (4.2) viser beregning av effektivverdi:

$$\begin{aligned} U_{rms} &= \sqrt{\tfrac{1}{2\pi}\int\limits_0^{2\pi} u^2\cdot d\omega t} \\ I_{rms} &= \sqrt{\tfrac{1}{2\pi}\int\limits_0^{2\pi} i^2\cdot d\omega t} \end{aligned} \tag{4.2}$$

Et bløttjernsinstrument vil måle effektivverdien av en strøm eller en spenning. De fleste digitale måleinstrumenter er i stand til å måle sann effektivverdi og er merket True RMS. Dette er imidlertid en sannhet med visse modifikasjoner. Dersom et signal inneholder tilstrekkelig mange høyfrekvente komponenter, vil ethvert digitalt instrument vise feil, mens et bløttjernsinstrument alltid viser sann RMS-verdi.

Eksempel 1 *En spenningskilde gir ut en sinusformet spenning med en amplitude på* 5 *V. Hva vil et dreiespoleinstrument uten likeretting vise (instrumentet er innstilt på DC)? Hva vil et bløttjernsinstrument vise?*

Løsning:

Vi definerer spenningen som

$$u = 5\sin(\omega t)$$

Dette tilsvarer et sinusformet vekselspenningssignal med en amplitude på 5 V. For å finne avlesningen på dreiespoleinstrumentet, anvendes formel (4.1):

$$U_{mid} = \frac{1}{2\pi}\int_0^{2\pi} 5\sin(\omega t)\,d\omega t = \frac{5}{2\pi}\left[\int_0^{\pi}\sin(\omega t)\,d\omega t - \int_{\pi}^{2\pi}\sin(\omega t)\,d\omega t\right] = 0$$

Dreiespoleinstrumentet vil bare stå og vibrere frem og tilbake rundt nullpunktet uten å gi noe utslag. For å finne utslaget på bløttjernsinstrumentet, anvendes formel (4.2):

$$U_{RMS} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} 25\sin^2(\omega t)\,d\omega t} = \sqrt{\frac{25}{2\pi}\int_0^{2\pi}\sin^2(\omega t)\,d\omega t}$$

For oversiktens skyld, beregner vi først integralet. Det er nok å integrere fra 0 til π, og deretter multiplisere med 2, siden uttrykket inni integralet vil danne to symmetriske ”kamelpukler”:

$$\begin{gathered}
\int_0^{2\pi} \sin^2(\omega t)\, d\omega t = 2\int_0^{\pi} \sin^2(\omega t)\, d\omega t \\
\int_0^{\pi} \sin^2(\omega t)\, d\omega t = \left[\tfrac{1}{2}(\omega t) - \tfrac{1}{4}\sin(2\omega t)\right]_0^{\pi} = \tfrac{\pi}{2} \\
\int_0^{2\pi} \sin^2(\omega t)\, d\omega t = \pi
\end{gathered}$$

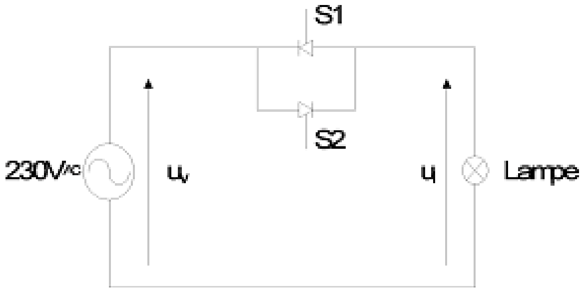
Dermed blir effektivverdien av signalet

$$U_{RMS} = \sqrt{\frac{25}{2\pi}\pi} = \sqrt{\frac{25}{2}} = \frac{5}{\sqrt{2}}\,\mathrm{V}$$

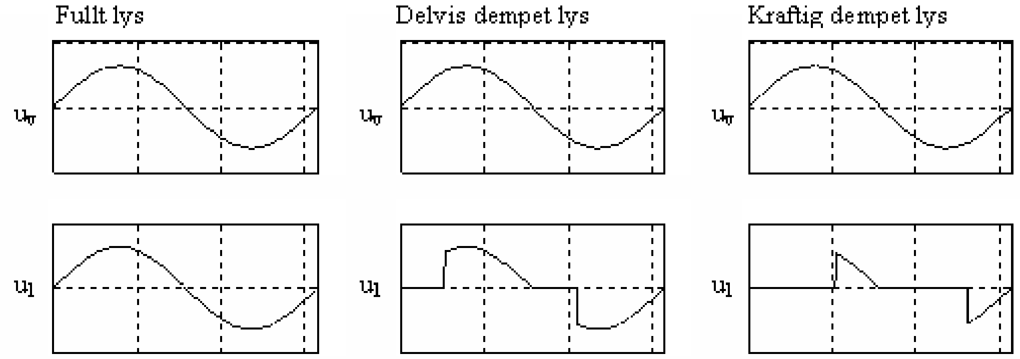
som stemmer overens med regelen som sier at effektivverdien av et sinusformet signal er lik amplitudeverdien delt på $\sqrt{2}$.

4.1 Innsnittstyring

Den enkleste form for lysdimmere benytter seg av innsnittstyring. Koblingsskjema er vist på figur 4.1. De to tyristorene øverst på figuren er koblet i antiparallell og slipper strøm gjennom i hver sin halvperiode. Dersom svitsjene tennes umiddelbart etter spenningens nullgjennomgang, vil lampen lyse med full styrke. Hvis tenningen forsinkes, vil lyset avta ved at det skjer et innsnitt i lampespenningens kurveform. Dette er vist på figur 4.2.



Figur 4.1: Lysdimmer med innsnittstyring



Figur 4.2: Spenningskurver for forskjellig utstyring av lysdimmer med innsnittstyring

På grunn av den uregelmessige kurveformen på utgangen av denne type lysdimmer, egner den seg best til vanlige glødelamper. Utstyr med reaktorspoler (strømbegrensende spoler) eller transformatorer, slik som lavvolts glødelamper (halogenlamper) og lysrør, vil kunne bli ekstra belastet på grunn av

utgangsspenningens skarpe kurveform. Denne kurveformen kan også være opphav til støy på det lokale nettet, samt radiostøy.
Øyeblikksverdien av nettspenningen kan uttrykkes som

$$u_v = U_m \sin(\omega t) \tag{4.3}$$

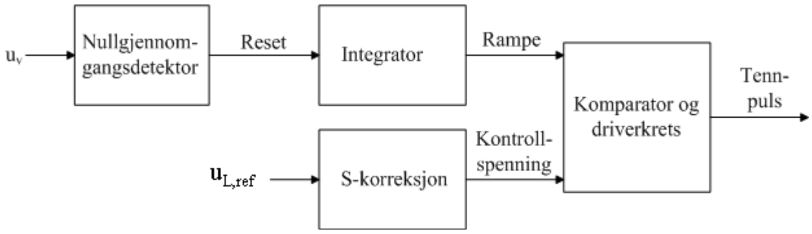
:På bakgrunn av dette kan man sette opp et uttrykk for lampespenningens effektivverdi:

$$U_L = U_m \sqrt{\frac{1}{\pi} \int_{\alpha}^{\pi} \sin^2(\omega t)\, d\omega t} = U_v \sqrt{\frac{2\pi + \sin(2\alpha) - 2\alpha}{2\pi}} \tag{4.4}$$

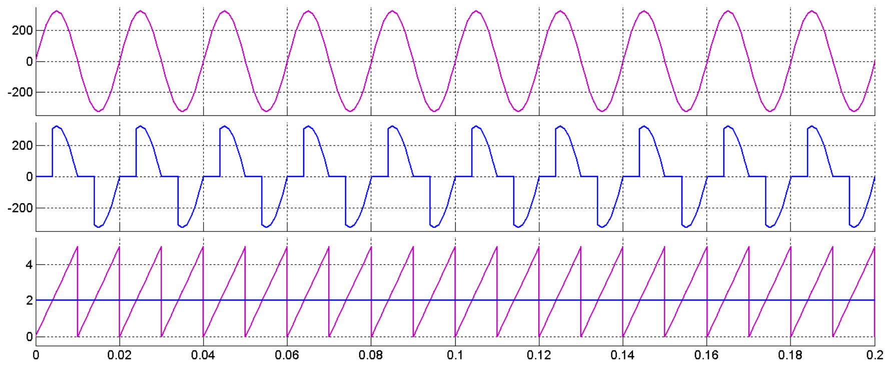
Lampespenningen som funksjon av styrevinkelen er altså:

$$U_L(\alpha) = U_v \sqrt{\frac{2\pi + \sin(2\alpha) - 2\alpha}{2\pi}} \tag{4.5}$$

Figur 4.3 viser kontrollkretsen til lysdimmeren. En nullgjennomgangsdetektor nullstiller integratoren ved hver nullgjennomgang i nettspenningen. Når rampespenningen er høyere enn kontrollspenningen, sendes en tennpuls til tyristorene. Dette er illustrert på figur 4.4.

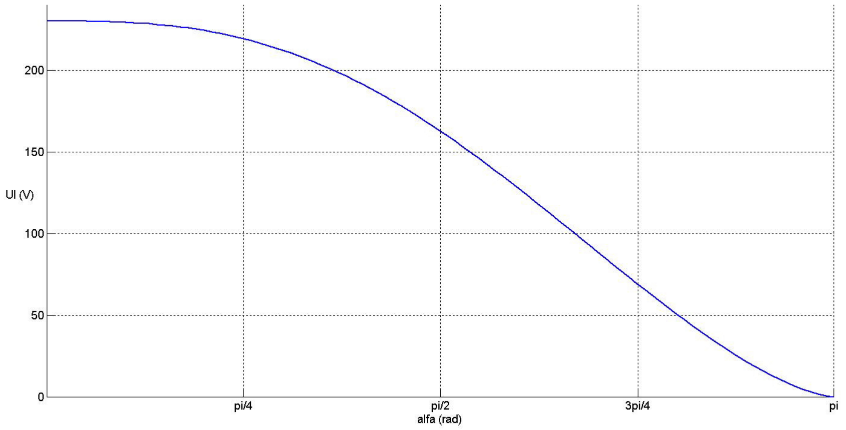


Figur 4.3: Kontrollkrets for innsnittstyring



Figur 4.4: Styresignaler for innsnittstyring. Øverst: Inngangsspenning, i midten: utgangsspenning, nederst: kontrollspenning og rampespenning

Figur 4.5 viser utgangsspenningen for en lysdimmer med innsnittstyring ved ulike styrevinkler.



Figur 4.5: Lampespenningen som funksjon av styrevinkelen for en lysdimmer med innsnittstyring

Lampeeffekten er gitt ved formel (4.6):

$$P_L\left(\alpha\right) = \frac{U_L^2\left(\alpha\right)}{R_L} = \frac{U_v^2}{R_L}\frac{2\pi + \sin\left(2\alpha\right) - 2\alpha}{2\pi} = P_N\frac{2\pi + \sin\left(2\alpha\right) - 2\alpha}{2\pi} \tag{4.6}$$

Eksempel 2 *En lysdimmer tilkoblet et* $230\,\mathrm{V}$ *nett med en frekvens på* $50\,\mathrm{Hz}$ *benytter seg av innsnittstyring, som vist på figur 4.2. Den er tilkoblet ei* $60\,\mathrm{W}$ *lampe. Hvor høy blir effektivverdien av utgangsspenningen og lampeeffekten hvis dimmeren kobler inn (a)* $2,5\,\mathrm{ms}$ *etter nullgjennomgang, eller (b)* $7,5\,\mathrm{ms}$ *etter nullgjennomgang?*

Løsning:
Den innkommende nettspenningen er

$$U_v = 230\,\mathrm{V}$$

$$U_L\left(\alpha\right) = U_v\sqrt{\frac{2\pi + \sin\left(2\alpha\right) - 2\alpha}{2\pi}}$$

a)
$2,5\,\mathrm{ms}$ tilsvarer en tidsvinkel $\omega t = 45\,^\circ$ eller $\frac{\pi}{4}$ radianer.

Utgangsspenningen blir da

$$U_L\left(\frac{\pi}{4}\right) = U_v\sqrt{\frac{2\pi + \sin(2\alpha) - 2\alpha}{2\pi}} = 230 \cdot \sqrt{\frac{2\pi + \sin\left(2 \cdot \frac{\pi}{4}\right) - 2 \cdot \frac{\pi}{4}}{2\pi}} = 219\,\mathrm{V}$$

Lampeeffekten er

$$P_L\left(\frac{\pi}{4}\right) = P_N\frac{2\pi + \sin(2\alpha) - 2\alpha}{2\pi} = 60 \cdot \frac{2\pi + \sin\left(2 \cdot \frac{\pi}{4}\right) - 2 \cdot \frac{\pi}{4}}{2\pi} = 54,5\,\mathrm{W}$$

b)
$7,5\,\mathrm{ms}$ tilsvarer en tidsvinkel $\omega t = 135\,°$ eller $\frac{3\pi}{4}$ radianer. Effektivverdien av utgangsspenningen blir Utgangsspenningen blir da

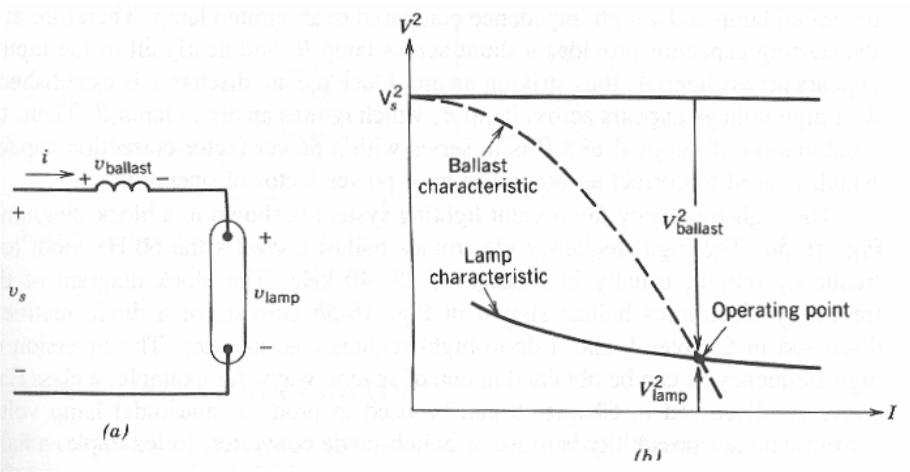
$$U_L\left(\frac{3\pi}{4}\right) = 230 \cdot \sqrt{\frac{2\pi + \sin\left(2 \cdot \frac{3\pi}{4}\right) - 2 \cdot \frac{3\pi}{4}}{2\pi}} = 69,3\,\mathrm{V}$$

Lampeeffekten er

$$P_L\left(\frac{3\pi}{4}\right) = 60 \cdot \frac{2\pi + \sin\left(2 \cdot \frac{3\pi}{4}\right) - 2 \cdot \frac{3\pi}{4}}{2\pi} = 5,45\,\mathrm{W}$$

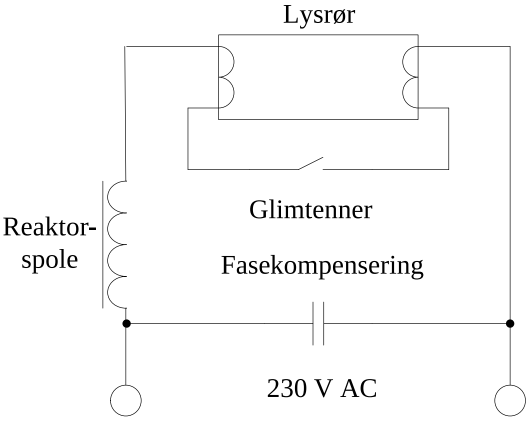
4.2 Lysrør med elektromagnetisk ballast

Tradisjonelt er lysrørene utstyrt med en reaktorspole for å gi en stabil drift. Et lysrør benytter seg av en lysbue, og lysbuer har en omvendt strøm/spenningskarakteristikk. Det betyr at spenningen øker med minkende strøm, og omvendt. Dette gir en svært ustabil drift, og en induktans (reaktorspole) i serie med lysrøret vil gi et stabilt arbeidspunkt. Dette er vist på figur 4.6. Kretsen vil ha en konstant spenning og strøm, gitt av skjæringspunktet mellom den heltrukne linjen (lysrøret) og den stiplede (reaktorspolen).



Figur 4.6: Lysrør med reaktorspole i serie

En vanlig kobling av lysrør er vist på figur 4.7. Denne ballastkretsen innholder både funksjoner for stabilisering og tenning av lysrørene.



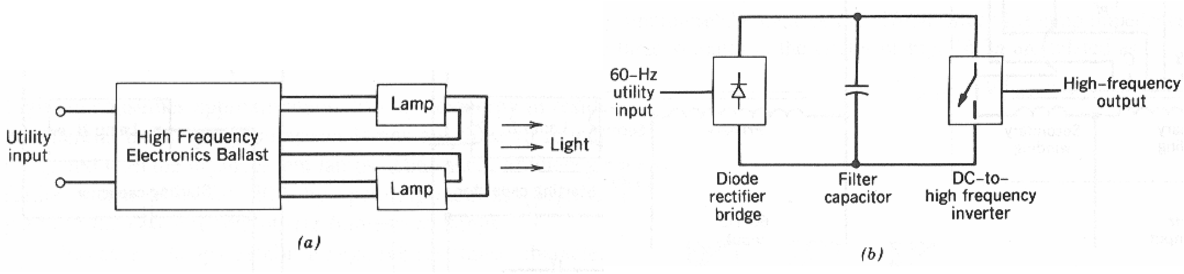
Figur 4.7: Koblingsskjema for lysrør med ballast

Når strømmen slås på, er glimtenneren lukket, og strømmen går gjennom begge glødekatodene. Disse varmes opp, og deretter åpner glimtenneren, og den induktive reaktorspolen skaper en spenningspuls som tenner lysrøret. Reaktorspolen fungerer nå som en induktiv strømbegrenser. En fasekompenseringskondensator er plassert i parallell med kretsen for å redusere det reaktive effektforbruket.

4.3 Lysrør med elektronisk ballast med innebygd dimming

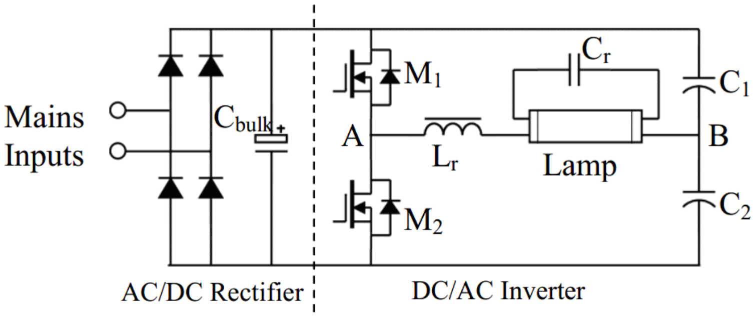
Den elektromagnetiske ballasten gir ingen mulighet for dimming av lysrørene. I dag er det mer og mer vanlig å benytte en elektronisk ballast som gir lysrørene en frekvens på 25kHz eller mer. Dette gir en økning i optisk virkningsgrad på $20 - 30$ % sammenlignet med 50Hz. Dette skyldes at utstrålingen fra lysrøret holdes mer konstant fordi det fluorescerende belegget på innsiden av rørene har en viss treghet. For øvrig er ikke øyet i stand til å oppfatte høyfrekvent flimmer, så lyset oppfattes som konstant.

En slik elektronisk ballast vil kreve mindre plass og være mer energieffektiv enn en tradisjonell elektromagnetisk, som tidligere beskrevet. Siden lampespenning og -strøm på kretsen på figur 4.8 kan reguleres, gir en slik elektronisk ballast også mulighet for dimming av lysrørene, i motsetning til kretsen på figur 4.7, som har konstant lysstyrke.



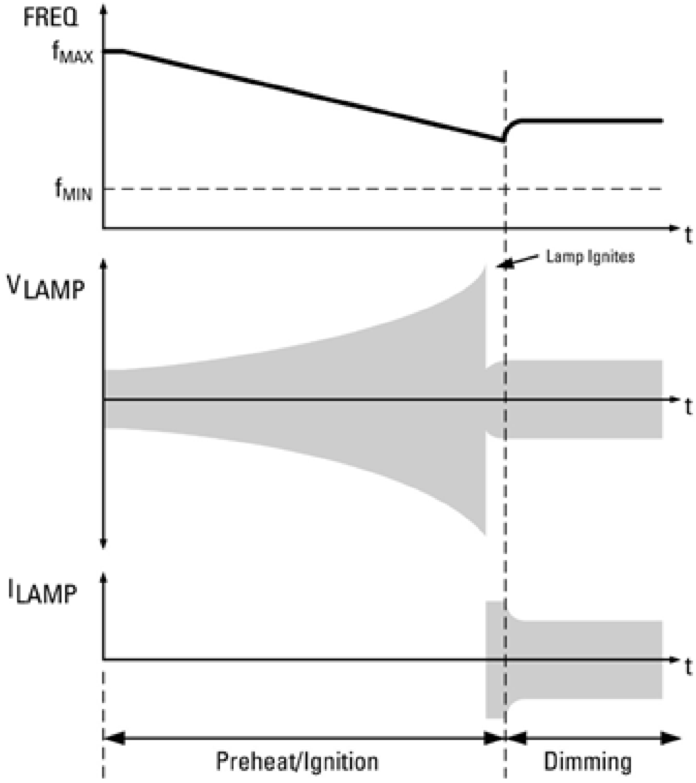
Figur 4.8: Blokkdiagram av elektronisk ballast for lysrør med mulighet for dimming

Figur 4.9 viser et detaljert prinsippskjema for energikretsen i en elektronisk ballast. I tillegg kommer en styrekrets som gir tennsignaler til transistorene M_1 og M_2. Nettspenningen som mates inn på ballasten, likerettes gjennom ei likeretterbru med fire dioder. Filterkondensatoren C_{bulk} sørger for at likespenningen U_d blir mest mulig glatt. Kondensatorene C_1 og C_2 er like store og fungerer som en spenningsdeler som gjør at punkt B på figur 4.9 har et potensial på $0,5U_d$. Transistorene M_1 og M_2 svitsjes vekselvis; når M_1 leder, sperrer M_2, og vice versa. Det betyr at punkt A har en spenning som skifter mellom U_d og 0. Spenningen mellom A og B vil da veksle mellom $+0,5U_d$ og $-0,5U_d$. Mellom disse to punktene ligger en reaktorspole L_r i serie med lysrørets ene glødekatode, en kondensator C_r og lysrørets andre glødekatode. Spolen L_r og kondensatoren C_r danner en resonanskrets.



Figur 4.9: Prinsippskisse for elektronisk ballast til lysrør

Når kretsen aktiveres, legges en høy svitsjefrekvens over transistorene, slik det er vist på figur 4.10. Lampespenningen tilsvarer spenningen over kondensatoren C_r og er moderat. Svitsjefrekvensen avtar gradvis og nærmer seg resonansfrekvensen til L_r og C_r. Dette gjør at lampespenningen øker kraftig, helt til lysrøret tenner. Et tent lysrør har svært lav impedans, noe som fører til at C_r blir kortsluttet. Resonanskretsen består nå av L_r og C_1 eller C_2 og vil ha en annen resonansfrekvens enn L_r og C_r. Lysstyrken reguleres ved å endre svitsjefrekvensen i forhold til den nye resonansfrekvensen.



Figur 4.10: Svitsjefrekvens, lampespenning og -strøm ved oppvarming, tenning og normal drift

Eksempel 3 *Et lysrør med elektronisk ballast forsynes fra et* $230\,\mathrm{V}$ *nett. Reaktorspolen* $L_r = 150\,\mathrm{mH}$*, og resonanskondensatoren* $C_r = 750\,\mathrm{pF}$*. Spenningsdelerne* $C_1 = C_2 = 10\,\mu\mathrm{F}$*. Glødekatodene har en total resistans* $R = 1500\,\Omega$*. Betrakt et tent lysrør som en ren kortslutning. Den opprinnelige svitsjefrekvensen* $f_{sw} = 40\,\mathrm{kHz}$ *og avtar gradvis. Ved* $f_{sw} = 17\,\mathrm{kHz}$ *tennes lysrøret og dimmes deretter ved at svitsjefrekvensen økes til* $f_{sw} = 25\,\mathrm{kHz}$*. Beregn lampespenningen ved oppstart og når lampa tenner. Beregn lampestrømmen umiddelbart etter tenning og etter at lampa er dimmet.*

Løsning:
Vekselretterspenninga er

$$U_{AB} = \frac{1}{2} \cdot \sqrt{2} \cdot U_v = \frac{1}{2} \cdot \sqrt{2} \cdot 230 = 162\,\mathrm{V}$$

Lampespenninga er gitt ved

$$U_L = U_{AB} \frac{-jX_{C_r}}{R + jX_{L_r} - jX_{C_r}} = U_{AB} \frac{-j\frac{1}{2\pi f_{sw} C_r}}{R + j2\pi f_{sw} L_r - j\frac{1}{2\pi f_{sw} C_r}}$$

Ved oppstart er $f_{sw} = 40\,\mathrm{kHz}$:

$$U_L = 162 \cdot \frac{-j\frac{1}{2\pi \cdot 40000 \cdot 750 \cdot 10^{-12}}}{1500 + j2\pi \cdot 40000 \cdot 0.15 - j\frac{1}{2\pi \cdot 40000 \cdot 750 \cdot 10^{-12}}} = 26,6\,\mathrm{V}$$

Ved tenning er $f_{sw} = 17\,\text{kHz}$:

$$U_L = 162 \cdot \frac{-j\frac{1}{2\pi \cdot 17000 \cdot 750 \cdot 10^{-12}}}{1500 + j2\pi \cdot 17000 \cdot 0.15 - j\frac{1}{2\pi \cdot 17000 \cdot 750 \cdot 10^{-12}}} = 528\,\text{V}$$

Etter tenning er lampestrømmen gitt ved

$$I_L = \frac{U_{AB}}{jX_{L_r} - jX_{C_1}} = \frac{U_{AB}}{j2\pi f_{sw} L_r - j\frac{1}{2\pi f_{sw} C_1}}$$

Før dimming er $f_{sw} = 17\,\text{kHz}$:

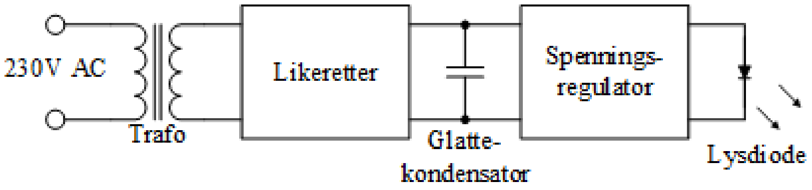
$$I_L = \frac{162}{j2\pi \cdot 17000 \cdot 0.15 - j\frac{1}{2\pi \cdot 17000 \cdot 10 \cdot 10^{-6}}} = 10\,\text{mA}$$

Etter dimming er $f_{sw} = 25\,\text{kHz}$:

$$I_L = \frac{162}{j2\pi \cdot 25000 \cdot 0.15 - j\frac{1}{2\pi \cdot 25000 \cdot 10 \cdot 10^{-6}}} = 6,9\,\text{mA}$$

4.4 Dimming av lysdioder

Blokkdiagrammet på figur 4.11 viser oppbyggingen til en lysdiode med dimming. Lysdioder opererer ved en spenning på noen få volt, og trafoen sørger for å senke spenningsnivået tilsvarende. Likeretteren med påfølgende glattekondensator forsyner spennningsregulatoren med en glatt likespenning. Lysstyrken fra en lysdiode er avhengig av strømmen gjennom dioden, og dermed også av påtrykt spenning fra dioden. Spenningsregulatoren har en fast inngangsspenning, men kan variere utgangsspenningen, og her ligger dimmefunksjonen. Jo høyere utgangsspenning, jo større lysstyrke.



Figur 4.11: Prinsippskisse for dimming av lysdioder

Eksempel 4 *Et armatur for dimming av en hvit lysdiode er utstyrt med en* $230/5\,\text{V}$ *transformator, etterfulgt av en enfase brulikeretter (kapittel 6.3.3)og en nedtransformerende DC-DC omformer (kapittel* **??***). Utgangsspenningen reguleres av pulsbreddeforholdet* d*. Beregn høyeste og laveste pulsbreddeforhold dersom lysdioden skal mates med* $0 - 3,5\,\text{V}$.

Løsning:
Utgangsspenningen fra likeretteren er

$$U_d = \sqrt{2}U_2 - 2 \cdot 0,7 = \sqrt{2} \cdot 5 - 2 \cdot 0,7 = 5,67\,\text{V}$$

Spenningsomsetningen i DC-DC omformeren er gitt ved

$$U_o = U_d \cdot d$$

Laveste utgangsspenning $U_o = 0\,\text{V}$:

$$d_{\text{min}} = \frac{U_o}{U_d} = \frac{0}{5,67} = 0$$

Høyeste utgangsspenning $U_o = 3,5\,\text{V}$:

$$d_{\text{max}} = \frac{U_o}{U_d} = \frac{3,5}{5,67} = 0,62$$

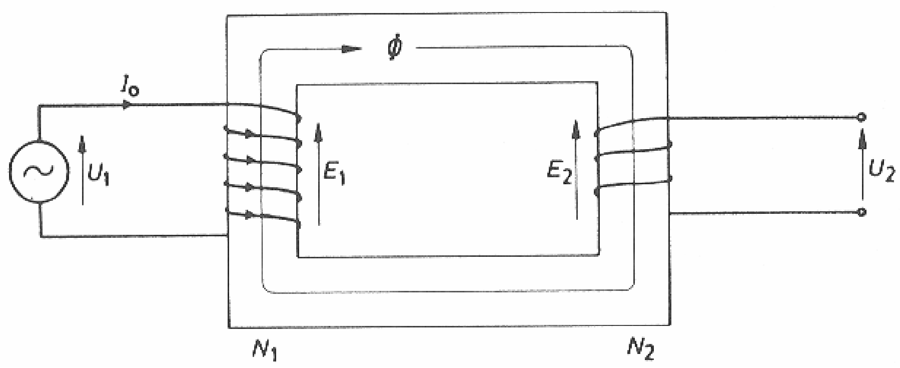
4.5 Øvingsoppgaver

1. Tegn kretsskjema for en lysdimmer med innsnittstyring.
2. En lysdimmer med innsnittstyring er tilkoblet et $230\,\mathrm{V}$ nett. Hva blir utgangspenningen dersom styrevinkelen $\alpha = 60\,^{\circ}$?
3. Hvilke fordeler og ulemper er knyttet til de ulike lysdimmerteknologiene?
4. Hvorfor øker lysutbyttet i et lysrør dersom en benytter en elektronisk ballast?

5 Transformatorer

5.1 Ideell transformator

På slutten av kapittel 1 så vi på koblede spoler. To spoler med sterk kobling (felles jernkjerne) kalles en transformator og regnes som en elektrisk maskin som overfører elektrisk energi til magnetisk energi og tilbake til elektrisk energi igjen. Figur 5.1 viser to slike koblede spoler. Den siden som får tilført energi, kalles primærsiden og er merket med indeks 1 (U_1, N_1, E_1), mens lastsiden kalles sekundærsiden og bruker indeks 2. Siden en transformator overfører både aktiv og reaktiv effekt, angir en transformatorens effekt i VA, kVA eller MVA.



Figur 5.1: Transformatorkobling

Dersom en sinusformet spenning påtrykkes primærviklingen på figur 5.1, vil det flyte en liten tomgangsstrøm I_0 (indeks 0 brukes for tomgangsstørrelser). Dette gir opphav til en magnetomotorisk kraft I_0N_1 som er opphav til kjernefluksen ϕ. En sinusformet fluks vil indusere spenninger i de to viklingene ut fra formel (5.1):

$$e = N\frac{d\phi}{dt} \tag{5.1}$$

Dette gir opphav til de to induserte spenningene E_1 og E_2. For en ideell transformator regner vi at

$$\begin{aligned} U_1 &= E_1 \\ U_2 &= E_2 \end{aligned} \tag{5.2}$$

Dersom en belaster transformatoren på figur 5.1, vil det flyte en strøm i sekundærkretsen. Den sterke magnetiske koblingen gjør at det også vil flyte en strøm på primærsiden. I en ideell transformator vil ingen effekt gå til spille. Dette gir at

$$\begin{aligned} P_1 &= P_2 \\ Q_1 &= Q_2 \\ S_1 &= S_2 \end{aligned} \tag{5.3}$$

Formel (5.3) medfører for det første at strøm og spenning er omvendt proporsjonale og for det andre at fasevinkelen vil være lik på primær- og sekundærsiden:

$$\begin{aligned} U_1I_1 &= U_2I_2 \\ \cos\varphi_1 &= \cos\varphi_2 \end{aligned} \tag{5.4}$$

Formel (5.1) indikerer at indusert spolespenning vil være proporsjonal med vindingstallet N, siden det er samme fluks (og fluksendringer) i begge viklingene. Dette, i kombinasjon med formel (5.2), innebærer at

$$\frac{U_1}{U_2} = \frac{E_1}{E_2} = \frac{N_1}{N_2} \tag{5.5}$$

som betyr at spenningsomsetningen i en transformator er proporsjonal med forholdet mellom vindingstallet på primær- og sekundærsiden. Ønsker en å transformere opp spenningen, lar en N_2 være større enn N_1. Vil en derimot transformere spenningen ned, lar en N_1 være større enn N_2.
Ut fra formel (5.4) kan en sette at

$$\frac{I_1}{I_2} = \frac{U_2}{U_1} \tag{5.6}$$

som igjen gir at

$$\frac{I_1}{I_2} = \frac{N_2}{N_1} \tag{5.7}$$

Dette innebærer at strømomsetningen er omvendt proporsjonal med spenningsomsetningen, og dermed også med forholdet mellom vindingstallene.
En transformator kan altså overføre effekt, den kan endre strøm- og spenningsomsetningen, og den gir galvanisk skille mellom to elektriske kretser. Forutsetningen for at formlene (5.2) - (5.7) gjelder, er at spenningene er sinusformede.

Eksempel 1 *En enfasetransformator med* 1000 *vindinger primært og* 200 *vindinger sekundært regnes som ideell. I et driftstilfelle er primær spenning* 240 *V og sekundær strøm* 10 *A. Beregn sekundær spenning og primær strøm.*

Løsning:
Formel (5.5) angir at spenningsomsetningen er lik forholdet mellom vindingstallene. Sekundær spenning blir da

$$U_2 = U_1 \frac{N_2}{N_1} = 240 \cdot \frac{200}{1000} = 48\,\mathrm{V}$$

Strømomsetningen er omvendt proporsjonal med forholdet mellom vindingstallene. Primær strøm blir dermed

$$I_1 = I_2 \frac{N_2}{N_1} = 10 \cdot \frac{200}{1000} = 2,0\,\mathrm{A}$$

Eksempel 2 *En ideell enfasetransformator har omsetning* $5400/240$ *V og sekundærvikling med* 200 *vindinger. Transformatoren avgir sekundært* 10 *kW ved* 200 *V og* $\cos\varphi_2 = 0,8$ *(induktiv). Beregn primært vindingstall, samt primær og sekundær strøm.*

Løsning:
Primært vindingstall blir

$$N_1 = N_2 \frac{U_{1N}}{U_{2N}} = 200 \cdot \frac{5400}{240} = 4500$$

Sekundær strøm blir

$$I_2 = \frac{P_2}{U_2 \cos\varphi_2} = \frac{10000}{200 \cdot 0,8} = 62,5\,\mathrm{A}$$

Primær strøm blir

$$I_1 = I_2 \frac{U_{2N}}{U_{1N}} = 62,5 \cdot \frac{240}{5400} = 2,8\,\mathrm{A}$$

5.2 Praktisk transformator i tomgang

Vi skal se nærmere på sammenhengen mellom indusert spenning og fluks for sinusformede spenninger.
I primærspolen vil indusert spenning være gitt ved

$$e_1 = N_1 \frac{d\phi}{dt} \tag{5.8}$$

Ved sinusformet fluks kan dette skrives som

$$e_1 = N_1 \frac{d}{dt} \left(\phi_{\max} \sin\left(\omega t\right)\right) = N_1 \phi_{\max} \omega \cos\left(\omega t\right) \tag{5.9}$$

hvor $\phi_{\max}$ er fluksens maksimalverdi.
Toppverdien av den induserte spenningen blir da

$$e_{1,\max} = N_1 \phi_{\max} \omega = N_1 \phi_{\max} 2\pi f \tag{5.10}$$

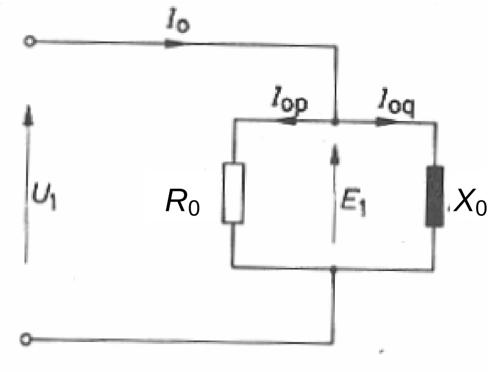
Effektivverdien blir

$$\begin{aligned} E_1 &= \tfrac{e_{1,\max}}{\sqrt{2}} = \tfrac{2\pi}{\sqrt{2}} N_1 \cdot f \cdot \phi_{\max} \\ E_1 &= 4,44 N_1 \cdot f \cdot \phi_{\max} \end{aligned} \tag{5.11}$$

For sekundærsiden gjelder tilsvarende:

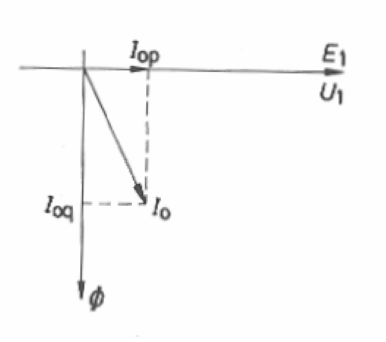
$$E_2 = 4,44 N_2 \cdot f \cdot \phi_{\max} \tag{5.12}$$

Formel (5.11) og (5.12) kalles gjerne transformatorligningen.
Jernkjernen i en transformator har lav reluktans og er ikke utstyrt med luftgap. Dette gjør at kjernen ved tomgang lett går i metning, og magnetisk hysterese er opphav til varmetap i kjernen. Dessuten vil det vekslende magnetfeltet indusere virvelstrømmer i jernkjernen. Selv om disse strømmene er relativt små, vil de også bidra til tap i kjernen. En transformator i tomgang kan betraktes som en enkelt spole med jernkjerne, og den opptrer i hovedsak som en induktans, sett fra nettet.
Figur 5.2 viser et ekvivalentskjema for en transformator i tomgang. Den ekvivalente resistansen R_0 skyldes hysterese og virvelstrømmer i kjernen, mens den ekvivalente reaktansen X_0 skyldes magnetiseringen av kjernen. Tomgangsstrømmen I_0 deler seg i en aktiv komponent I_{0p} (tap) og en reaktiv komponent I_{0q} (magnetisering).



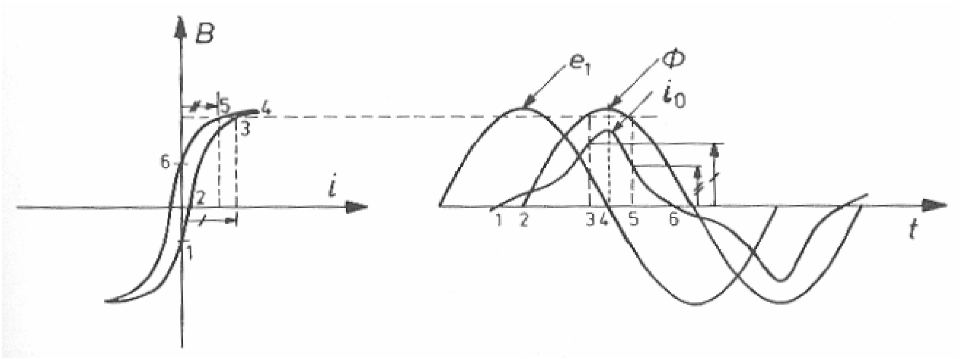
Figur 5.2: Ekvivalentskjema for enfasetransformator i tomgang

Figur 5.3 fremstiller et viserdiagram for strøm, spenning og fluks i tomgang. En ser av figuren at I_{0q} er mye større enn I_{0p}. Tomgangssstrømmen er altså i hovedsak en reaktiv strøm som ligger nærmere 90 grader etter spenningen.



Figur 5.3: Viserdiagram for strøm, spenning og fluks i tomgang

Som før nevnt, vil kjernen lett gå i metning ved tomgang. Figur 5.4 illustrerer dette. Figuren til venstre viser jernets hysteresesløyfe, mens tidsdiagrammet til høyre viser påtrykt spenning, fluks og magnetiseringsstrøm (tomgangsstrøm). En ser at spenning og fluks er sinusformet, mens tomgangsstrømmen for en karakteristisk klokkelignende form med en betydelig tredjeharmonisk strømkomponent. Jo høyere primærspenningen er, jo mer vil jernet gå i metning, og tomgangsstrømmen vil få en enda mer forvrengt kurveform.



Figur 5.4: Hysteresesløyfe, samt kurver for påtrykt spenning, fluks og magnetiseringsstrøm ved tomgang

Eksempel 3 *En enfasetransformator trekker i tomgang* $0,50$ *A og* 50 *W ved* 250 *V og* 50 *Hz. Primært vindingstall er* 2000*.*

Beregn effektfaktoren $\cos\varphi_0$*, tomgangsstrømmens aktive og reaktive komponent,* R_0 *og* X_0 *i en parallellekvivalent, samt nødvendig jerntverrsnitt dersom flukstettheten ikke skal overstige* $1,6$ *T.*

Løsning:
Effektfaktoren i tomgang er

$$\cos\varphi_0 = \frac{P_0}{U_1 I_0} = \frac{50}{250 \cdot 0,50} = 0,40$$

Den aktive strømkomponenten:

$$I_{0p} = I_0 \cos\varphi_0 = 0,50 \cdot 0,40 = 0,20\,\mathrm{A}$$

Den reaktive strømkomponenten:

$$I_{0q} = I_0 \sin\varphi_0 = 0,50 \cdot \sqrt{1 - 0,40^2} = 0,46\,\mathrm{A}$$

Ekvivalent tomgangsresistans:

$$R_0 = \frac{P_0}{{I_{0p}}^2} = \frac{50}{0,20^2} = 1250\ \Omega$$

Ekvivalent tomgangsreaktans:

$$X_0 = \frac{U_1}{I_{0q}} = \frac{250}{0,46} = 544\ \Omega$$

Vi benytter transformatorligningen for å finne maksimal fluks:

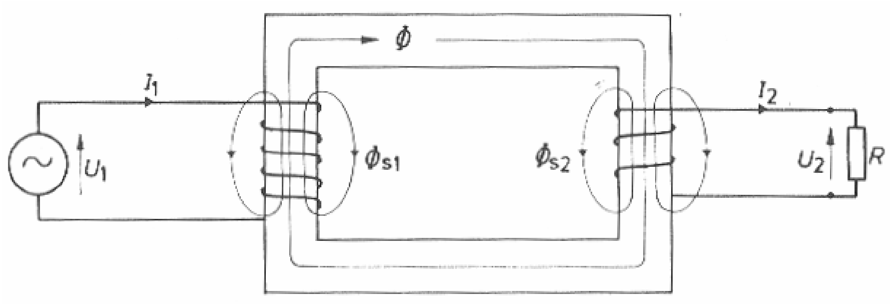
$$E_1 = 4,44 \cdot N_1 \cdot f \cdot \phi_{\max} = 4,44 \cdot N_1 \cdot f \cdot B_{\max} \cdot A$$

Denne løses med hensyn på tverrsnittet A:

$$A = \frac{E_1}{4,44 \cdot N_1 \cdot f \cdot B_{\max}} = \frac{250}{4,44 \cdot 2000 \cdot 50 \cdot 1,6} = 3,5\,\mathrm{cm}^2$$

5.3 Praktisk transformator ved belastning

I tillegg til tomgangsstrømmen , vil også andre forhold gjøre seg gjeldende i en transformator, forhold som gjør at den vil avvike fra en ideell transformator. Figur 5.5 viser at hver vikling vil ha en viss lekkfluks som går utenom fellesfluksen. Dermed vil hver av viklingene ha en viss lekkreaktans X_1 og X_2 for henholdsvis primær- og sekundærsiden. I tillegg vil viklingene ha en viss resistans, og den betegnes henholdsvis R_1 og R_2, avhengig om det er primær- eller sekundærsiden.

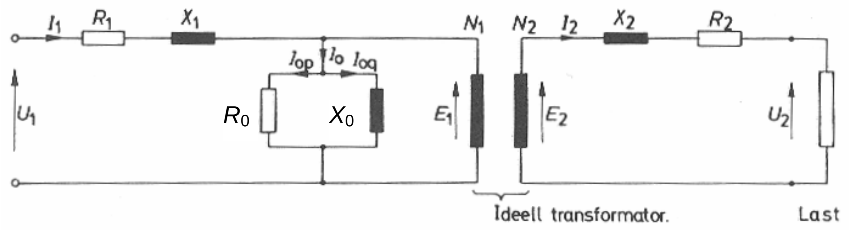


Figur 5.5: Praktisk transformator ved belastning

Figur 5.6 viser et komplett ekvivalentskjema for enfasetransformatoren. Ved belastning vil det oppstå et spenningsfall over R_1 og X_1, samt R_2 og X_2, og da gjelder ikke lenger formel (5.2):

$$\begin{aligned} U_1 &> E_1 \\ E_2 &> U_2 \end{aligned} \tag{5.13}$$

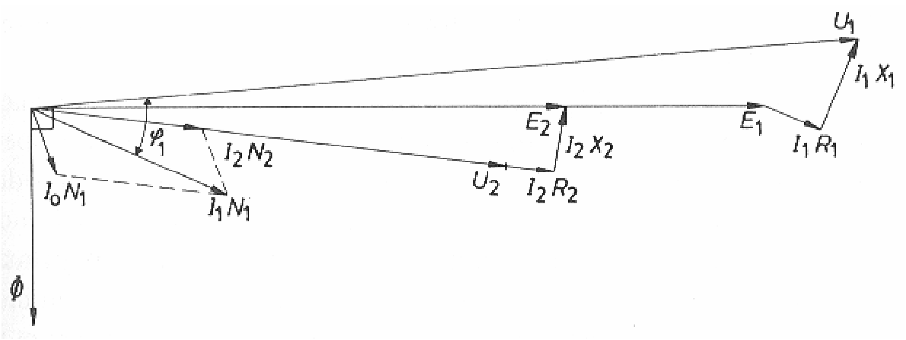
Ved tomgang vil det ikke gå noen strøm gjennom den ideelle transformatoren på figur 5.6, og tomgangsstrømmen er så liten at en kan se bort fra spenningsfallet over R_1 og X_1. Figur 5.2 er med andre ord en forenklet utgave av figur 5.6.



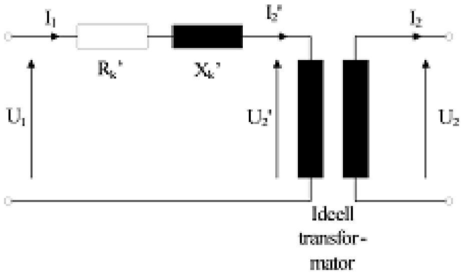
Figur 5.6: Ekvivalentskjema for belastet transformator

Ved belastning må en imidlertid ta hensyn til alle spenningsfall. Figur 5.7 presenterer et viserdiagram for en belastet transformator. En ser at det er et spenningsfall mellom primær klemmespenning U_1 og indusert spenning E_1. forholdet mellom de induserte spenningene E_1 og E_2 vil kun være bestemt av forholdet mellom vindingstallene. Et nytt spenningsfall finner sted mellom indusert sekundærspenning E_2 og sekundær klemmespenning U_2. Primærstrømmen I_1 er vektorsummen av magnetiseringsstrømmen I_0 og belastningsstrømmen $I_2{}'$.
Ved kraftig belastning vil laststrømmen $I_2{}'$ bli så mye høyere enn tomgangsstrømmen I_0, at en kan ignorere sistnevnte. Hvis en i tillegg regner om de sekundære impedanskomponentene og flytter den over på primærsiden , ser ekvivalentskjemaet ut som på figur 5.8.
Når en skal regne om den sekundære spenningen U_2 til primær referanse $U_2{}'$, multipliserer en med omsetningsforholdet:

$$U_2{}' = U_2 \frac{N_1}{N_2} \tag{5.14}$$



Figur 5.7: Viserdiagram for belastet transformator



Figur 5.8: Forenklet ekvivalent for enfasetransformator med ideell transformator

For den sekundære strømmen I_2 referert primærsiden $I_2{}'$, bruker en det omvendte omsetningsforholdet:

$$I_2{}' = I_2 \frac{N_2}{N_1} \tag{5.15}$$

Når en skal regne om de sekundære impedanskomponentene til primær referanse, må en bruke omsetningsforholdet i kvadrat:

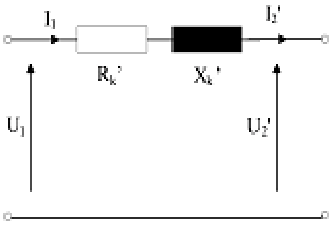
$$\begin{aligned} R_2{}' &= R_2 \left(\frac{N_1}{N_2}\right)^2 \\ X_2{}' &= X_2 \left(\frac{N_1}{N_2}\right)^2 \end{aligned} \tag{5.16}$$

Deretter summerer en impedanskomponentene:

$$\begin{aligned} R_k{}' &= R_1 + R_2{}' \\ X_k{}' &= X_1 + X_2{}' \end{aligned} \tag{5.17}$$

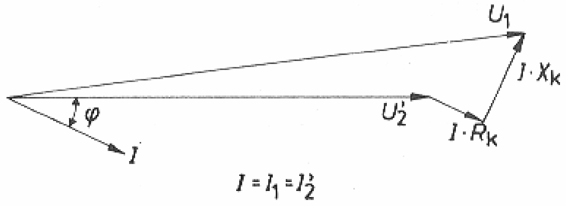
Indeks k angir at dette er transformatorens kortslutningsimpedans, og apostrof-tegnet forteller at impedansen er referert primærspenningen .

En ytterligere forenkling av kortslutningsekvivalenten består i å fjerne den ideelle transformatoren. Da står en igjen med skjemaet på figur 5.9. Kretsen har bare en strøm, $I_1 = I2\,'$, og bare ett spenningsfall, nemlig over $R_k\,'$ og $X_k\,'$.



Figur 5.9: Forenklet ekvivalent for enfasetransformator uten ideell transformator

Viserdiagram for denne forenklede kretsen er vist på figur 5.10.



Figur 5.10: Viserdiagram for forenklet ekvivalent

Eksempel 4 *En enfasetransformator på* 50 *kVA har vindingstall* $N_1 = 5000$ *og* $N_2 = 100$*. Vekselstrømsresistansene i viklingene er* $R_1 = 5,0\ \Omega$ *og* $R_2 = 0,0020\ \Omega$*. Kortslutningsimpedansen* $Z_k\,' = 50\ \Omega$*. Tomgangsstrømmen er neglisjerbar.*

Beregn kortslutningsresistans og kortslutningsreaktans. Beregn strømvarmetapet i henholdsvis sekundærvikling og primærvikling ved en sekundær strøm på 500 *A. Beregn primær og sekundær kortslutningsstrøm ved primær spenning* 20000 *V.*

Løsning:
Transformatorens kortslutningsresistans er gitt ved

$$R_k\,' = R_1 + R_2\left(\frac{N_1}{N_2}\right)^2 = 5,0 + 0,0020\cdot\left(\frac{5000}{100}\right)^2 = 10\ \Omega$$

Kortslutningsreaktansen er gitt ved

$$X_k\,' = \sqrt{(Z_k\,')^2 - (R_k\,')^2} = \sqrt{50^2 - 10^2} = 49\ \Omega$$

Ved sekundær strøm 500A blir primærstrømmen

$$I_1 = I_2\,' = I_2\frac{N_2}{N_1} = 500\cdot\frac{100}{5000} = 10\,\mathrm{A}$$

Strømvarmetap i henholdsvis sekundær- og primærvikling:

$$P_{b,2} = R_2 I_2\,^2 = 0,0020\cdot 500^2 = 500\,\mathrm{W}$$

$$P_{b,1} = R_1 I_1\,^2 = 5,0\cdot 10^2 = 500\,\mathrm{W}$$

Primær kortslutningsstrøm:

$$I_{1k} = \frac{U_1}{Z_k\,'} = \frac{20000}{50} = 400\,\mathrm{A}$$

Sekundær kortslutningsstrøm:

$$I_{2k} = I_{1k}\frac{N_1}{N_2} = 400 \cdot \frac{5000}{100} = 20\,\mathrm{kA}$$

Eksempel 5 *En enfasetransformator med omsetning* $1200/240$ *V trekker i tomgang* $5,0$ *A ved* $\cos\varphi_0 = 0,20$*. I et belastningstilfelle er sekundærstrømmen* 100 *A ved* $\cos\varphi_2 = 0,80$*. Se bort fra spenningsfall og beregn primærstrømmen.*

Løsning:
Belastningskomponenten av primærstrømmen er

$$I_2\,' = I_2\frac{N_2}{N_1} = 100 \cdot \frac{240}{1200} = 20\,\mathrm{A}$$

Den vektorielle summen av primærstrømmen finnes ved å regne realdelene for seg og de imaginære delene for seg:

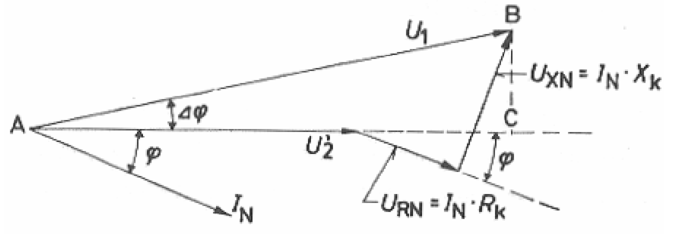
$$\begin{gathered}\vec{I}_1 = \vec{I}_0 + \vec{I}_2\,' = I_0\cos\varphi_0 + I_2\,'\cos\varphi_2 - j\left(I_0\sin\phi_0 + I_2\,'\sin\varphi_2\right)\\ = 5,0\cdot 0,20 + 20\cdot 0,80 - j\left(5,0\cdot 0,98 + 20\cdot 0,60\right) = (17 - j16,9)\ \mathrm{A}\\ I_1 = 24\,\mathrm{A}\end{gathered}$$

5.4 Relative spenningsfall

Det fremkommer av figur 5.10 at det vil være et spenningsfall ΔU mellom primærspenningen U_1 og sekundærspenningen sett fra primærsiden ($U_2\,'$). Amplituden av dette spenningsfallet utgjøres av forskjellen i lengde på vektorene $\vec{U}_1$ og $\vec{U}_2\,'$. Effektivverdien av ΔU tilsvarer

$$\Delta U = |U_1| - |U_2\,'| \tag{5.18}$$

Man må altså regne ut U_1 og $U_2\,'$ på kompleks form, for så å regne ut absoluttverdiene. Siden de nesten ligger i fase med hverandre, fins det en forenklet beregningsmåte som gir et tilnærmet spenningsfall med ganske stor nøyaktighet. Figur 5.11 viser hvordan man kan projisere U_1 ned på linjen i forlengelsen av $U_2\,'$. En ser at linjestykkene AB og AC er tilnærmet like lange. Dermed vil spenningsfallet ΔU være tilnærmet likt avstanden fra spissen av $U_2\,'$ til punktet C. Videre ser en at fasevinkelen φ forkommer tre steder på figuren: De to som er avmerket, samt mellom linjen BC og reaktansspenningsfallet U_{xN}.



Figur 5.11: Projeksjonsmetode for beregning av spenningsfall

Det tilnærmede spenningsfallet kan derfor beregnes ved hjelp av enkle trigonometriske uttrykk, slik det er definert i formel (5.19):

$$\Delta U \approx I_1 R_k{}' \cos\varphi_2 + I_1 X_k{}' \sin\varphi_2 \tag{5.19}$$

Det er vanlig å angi spenningsfall som en relativ verdi, ofte oppgitt i %. En beregner da forholdet mellom spenningsfall ved merkestrøm og merkespenning, og en skiller mellom relativ resistansspenning, relativ reaktansspenning og relativ impedansspenning eller kortslutningsspenning.
Relativ resistansspenning er er gitt ved

$$e_r = \frac{I_{1N} R_k{}'}{U_{1N}} \tag{5.20}$$

Relativ reaktansspenning e_x blir

$$e_x = \frac{I_{1N} X_k{}'}{U_{1N}} \tag{5.21}$$

Relativ impedansspenning e_z eller kortslutningsspenning e_k blir

$$e_z = e_k = \frac{I_{1N} Z_k{}'}{U_{1N}} \tag{5.22}$$

Relative spenninger kan også uttrykkes i prosent:

$$e_k = \frac{I_{1N} Z_k{}'}{U_{1N}} 100\% \tag{5.23}$$

En kan også velge sekundær merkespenning som referanse, men da må en regne om kortslutningsimpedansen til sekundær referanse:

$$R_k{}'' = R_k{}' \left(\frac{N_2}{N_1}\right)^2 \tag{5.24}$$

Da vil det relative spenningsfallet bli

$$e_r = \frac{I_{2N} R_k{}''}{U_{2N}} \tag{5.25}$$

Formel (5.19) kan også uttrykkes som et prosentuelt spenningsfall:

$$\Delta u\% = \frac{\Delta U}{U_{1N}} 100\% = \frac{I_1}{U_{1N}} \left(R_k{}' \cos\varphi_2 + X_k{}' \sin\varphi_2\right) 100\% \tag{5.26}$$

Vi innfører et nytt begrep, nemlig belastningsgraden n, som er forholdet mellom laststrøm og merkestrøm:

$$n = \frac{I_1}{I_{1N}} = \frac{I_2}{I_{2N}} \tag{5.27}$$

Da kan formel (5.19) og (5.26) forenkles til

$$\Delta u\% = n \left(e_r \cos\varphi_2 + e_x \sin\varphi_2\right) 100\% \tag{5.28}$$

Denne forenklingen kan brukes med stor nøyaktighet så lenge kortslutningsspenningen e_k ikke er større enn 4 %.

Eksempel 6 *En enfasetransformator på* 1100 *VA har spenningsomsetning* $220/110$ *V, viklingsresistanser* $R_1 = 0,40\,\Omega$ *og* $R_2 = 0,10\,\Omega$ *og lekkreaktanser* $X_1 = 0,60\ \Omega$ *og* $X_2 = 0,15\ \Omega$*.*

Beregn $R_k\,'$*,* $X_k\,'$ *og* $Z_k\,'$*, samt prosentuelle spenninger* e_r*,* e_x *og* e_z*.*
Regn ut prosentuelt spenningsfall i transformatoren ved merkelast og $\cos\varphi_2 = 0,80$*.*
Regn ut primærspenningen ved sekundære verdier $U_2 = 100$ *V,* $I_2 = 8,0$ *A og* $\cos\varphi_2 = 0,60$*.*
Regn ut sekundærspenningen når primær spenning er 230 *V mens* $I_1 = 6,0$ *A og* $\cos\varphi_2 = 1,0$*.*

Løsning:
Kortslutningsimpedanskomponentene referert primærsiden blir:

$$\begin{aligned} R_k\,' &= R_1 + R_2\left(\tfrac{N_1}{N_2}\right)^2 = 0,40 + 0,10\cdot\left(\tfrac{220}{110}\right)^2 = 0,80\ \Omega \\ X_k\,' &= X_1 + X_2\left(\tfrac{N_1}{N_2}\right)^2 = 0,60 + 0,15\cdot\left(\tfrac{220}{110}\right)^2 = 1,2\ \Omega \\ Z_k\,' &= \sqrt{(R_k\,')^2 + (X_k\,')^2} = \sqrt{0,80^2 + 1,2^2} = 1,44\ \Omega \end{aligned}$$

Merkestrømmene blir

$$\begin{aligned} I_{1N} &= \tfrac{S_N}{U_{1N}} = \tfrac{1100}{220} = 5,0\,\mathrm{A} \\ I_{2N} &= \tfrac{S_N}{U_{2N}} = \tfrac{1100}{110} = 10\,\mathrm{A} \end{aligned}$$

De prosentuelle spenningene blir

$$\begin{aligned} e_r &= \tfrac{I_{1N}R_k\,'}{U_{1N}}100\% = \tfrac{5,0\cdot 0,80}{220}100\% = 1,82\% \\ e_x &= \tfrac{I_{1N}X_k\,'}{U_{1N}}100\% = \tfrac{5,0\cdot 1,2}{220}100\% = 2,73\% \\ e_z &= \tfrac{I_{1N}Z_k\,'}{U_{1N}}100\% = \tfrac{5,0\cdot 1,44}{220}100\% = 3,27\% \end{aligned}$$

Det prosentuelle spenningsfallet ved merkelast blir

$$\Delta u\% = n\,(e_r\cos\varphi_2 + e_x\sin\varphi_2)\,100\% = 1\cdot(1,82\cdot 0,80 + 2,73\cdot 0,60) = 3,1\%$$

Ved sekundære verdier $U_2 = 100$ V, $I_2 = 8,0$ A og $\cos\varphi_2 = 0,60$ blir spenningsfallet

$$\Delta u\% = n\,(e_r\cos\varphi_2 + e_x\sin\varphi_2)\,100\% = \frac{8,0}{10}\cdot(1,82\cdot 0,60 + 2,73\cdot 0,80) = 2,62\%$$

Da blir primærspenningen

$$U_1 = U_2\,' + \Delta U = U_2\frac{N_1}{N_2} + U_{1N}\frac{\Delta u\%}{100\%} = 100\cdot\frac{220}{110} + 220\cdot\frac{2,62}{100} = 200 + 5,8 = 205,8 \approx 206\,\mathrm{V}$$

Ved $I_1 = 6,0$ A og $\cos\varphi_2 = 1,0$ blir spenningsfallet

$$\Delta u\% = n\,(e_r\cos\varphi_2 + e_x\sin\varphi_2)\,100\% = \frac{6,0}{5,0}\cdot(1,82\cdot 1,0 + 2,73\cdot 0) = 2,18\%$$

Sekundær spenning ved primærspenning 230 V blir

$$U_2 = U_1\frac{N_2}{N_1} - U_{2N}\frac{\Delta u\%}{100\%} = 230\cdot\frac{110}{220} - 110\cdot\frac{2,18}{100} = 115 - 2,4 = 112,6 \approx 113\,\mathrm{V}$$

5.5 Tap og virkningsgrad

De aktive tapene ΔP i en transformator kan deles inn i tomgangstap P_0 og belastningstap P_b:

$$\Delta P = P_0 + P_b \tag{5.29}$$

Tomgangstapene finner sted i kjernen og kalles også jerntap. De skyldes hysterese og virvelstrømmer. Hysteresetapet er definert som

$$P_{hy} = k_1 f {\phi_{\max}}^2 \tag{5.30}$$

og virvelstrømstapet er definert som

$$P_{vi} = k_2 f^2 {\phi_{\max}}^2 \tag{5.31}$$

Disse tapene vil være konstante ved konstant frekvens og fluks.
Ifølge transformatorligningen vil spenningen være proporsjonal med fluksen ved konstant frekvens:

$$\begin{gathered} E = 4,44 \cdot N \cdot f \cdot \phi_{\max} \\ U = k \cdot \phi_{\max} \text{ for } U = E \end{gathered} \tag{5.32}$$

I et stivt nett vil frekvensen alltid være konstant. Hvis vi går ut fra at indusert spenning er tilnærmet lik klemmespenning, kan vi formulere tomgangstapene som

$$P_0 = \frac{{U_1}^2}{R_0} \tag{5.33}$$

som innebærer at tomgangstapene endrer seg med primærspenningen i kvadrat.
Belastningstapene skyldes både resistans i viklingene (likestrømstap P_{DC}) og tilleggstap som skyldes strømfortrengning og induserte virvelstrømmer i omkringliggende metalldeler (tilleggstap P_{till}) og kan skrives som

$$P_b = P_{DC} + P_{till} \tag{5.34}$$

Både likestrømstap og tilleggstap er strømvarmetap, og derfor kan belastningstapene formuleres som

$$P_b = {R_k}' I^2 \tag{5.35}$$

som innebærer at belastningstapene endrer seg med laststrømmen i kvadrat.
Tomgangstapene bestemmes ved effektmåling på en transformator med åpne sekundærklemmer og tilkoblet merkespenning på primærsiden . Belastningstapene bestemmes ved effektmåling på en transformator med kortsluttede sekundærklemmer, og primærspenningen justeres slik at transformatoren fører merkestrøm. Den spenningen som måles på primærsiden , vil da være transformatorens impedansspenningsfall ΔU_k, også kalt kortslutningsspenningsfall.
En kan da enkelt beregne relativ kortslutningsspenning:

$$e_k = e_z = \frac{\Delta U_k}{U_{1N}} 100\% \tag{5.36}$$

Disse målingene gjøres ved romtemperatur, mens viklingstemperaturen for en krafttransformator normalt sett vil ligge mye høyere. En velger derfor ofte 75°C som en referansetemperatur. Ved økt viklingstemperatur vil likestrømstapene øke fordi viklingsresistansen øker. Tilleggstapene vil derimot minke, fordi den økte resistansen i de omkringliggende metalldelene vil redusere de uønskede virvelstrømmene.
Formel 5.37 benyttes til å beregne størrelsen på belastningstapene ved normal driftstemperatur:

$$P_{b75} = P_{DC} \frac{235 + 75}{235 + \vartheta} + P_{till} \frac{235 + \vartheta}{235 + 75} \tag{5.37}$$

En kan da enkelt beregne transformatorens relative resistansspenningsfall:

$$e_r = \frac{I_{1N} R_k{}'}{U_{1N}} \frac{I_{1N}}{I_{1N}} 100\% = \frac{R_k{}' I_{1N}{}^2}{U_{1N} I_{1N}} 100\% = \frac{P_{b75}}{S_N} 100\% \tag{5.38}$$

Virkningsgraden η angir forholdet mellom tilført og avgitt aktiv effekt:

$$\eta = \frac{P_2}{P1} \tag{5.39}$$

Siden de samlede tapene ΔP utgjør differansen mellom tilført og avgitt aktiv effekt, kan virkningsgraden uttrykkes på følgende måter:

$$\eta = \frac{P_1 - \Delta P}{P_1} = \frac{P_2}{P_2 + \Delta P} \tag{5.40}$$

I formel (5.27) introduserte vi begrepet belastningsgrad, som er forholdet mellom laststrøm og merkestrøm. Siden avgitt effekt er proporsjonal med laststrømmen, må avgitt effekt også være proporsjonal med belastningsgraden. Av formel (5.35) kan vi trekke den slutning at belastningstapene må være proporsjonale ned kvadratet av belastningsgraden. Da kan avgitt effekt formuleres som

$$P_2 = n S_N \cos \varphi_2 \tag{5.41}$$

og de samlede tapene som

$$\Delta P = P_0 + P_b = P_0 + n^2 P_{b75} \tag{5.42}$$

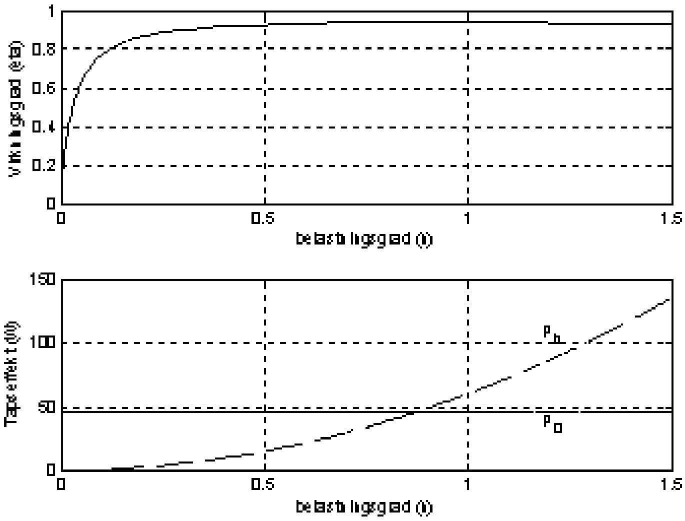
Ved å sette disse uttrykkene inn i formel (5.40), får vi et uttrykk for virkningsgraden som en funksjon av belastningsgraden:

$$\eta = \frac{P_2}{P_2 + \Delta P} = \frac{n S_N \cos \varphi_2}{n S_N \cos \varphi_2 + P_0 + n^2 P_{b75}} \tag{5.43}$$

Den belastningsgraden som gir maksimal virkningsgrad er gitt ved

$$n_m = \sqrt{\frac{P_0}{P_{b75}}} \tag{5.44}$$

Figur 5.12 viser virkningsgraden som funksjon av belastningsgraden. En legger merke til to ting: Transformatoren har en høy virkningsgrad over et stort belastningsområde, og virkningsgraden er maksimal når tomgangstapene og belastningstapene er like store.



Figur 5.12: Transformatorens virkningsgrad ved ulike belastninger

Eksempel 7 *En* 50 *kVA enfasetransformator med spenningsomsetning* $1000/200$ *V har følgende relative spenningsfall:* $e_r = 1,5\%$*,* $e_k = 4,5\%$*. Ved* $20\,^\circ\mathrm{C}$ *måles følgende resistanser:* $R_1 = 150\,\mathrm{m}\Omega$*,* $R_2 = 6,0\,\mathrm{m}\Omega$*. Ved samme temperatur måles et belastningstap på* $900\,\mathrm{W}$ *ved merkestrøm. Tomgangstapet måles til* $400\,\mathrm{W}$ *ved merkespenning.*

a. *Regn ut impedanskomponentene* $R_k{}'$*,* $X_k{}'$ *og* $Z_k{}'$*.*
b. *Regn ut likestrømstapet og tilleggstapet ved* $20\,^\circ\mathrm{C}$*.*
c. *Regn ut belastningstapet ved merkelast og* $75\,^\circ\mathrm{C}$*.*
d. *Regn ut virkningsgraden ved halv last og ved full last når* $\cos\varphi_2 = 0,8$ *induktiv.*

Løsning:
a.
Primær merkestrøm er

$$I_{1N} = \frac{S_N}{U_{1N}} = \frac{50000}{1000} = 50\,\mathrm{A}$$

Kortslutningsresistansen er

$$R_k{}' = \frac{U_{1N}}{I_{1N}} \cdot e_r = \frac{1000}{50} \cdot 0,015 = 0,30\,\Omega$$

Relativt reaktansspenningsfall er

$$e_x = \sqrt{e_k{}^2 - e_r{}^2} = \sqrt{4,5^2 - 1,5^2} = 4,24\%$$

Kortslutningsreaktansen er

$$X_k{}' = \frac{U_{1N}}{I_{1N}} \cdot e_x = \frac{1000}{50} \cdot 0,0424 = 0,85\,\Omega$$

Kortslutningsimpedansen er

$$Z_k{}' = \frac{U_{1N}}{I_{1N}} \cdot e_k = \frac{1000}{50} \cdot 0,045 = 0,90\,\Omega$$

b.
Sekundær merkestrøm er

$$I_{2N} = I_{1N}\frac{U_{1N}}{U_{2N}} = 50 \cdot \frac{1000}{200} = 250\,\mathrm{A}$$

Likestrømstapet er

$$P_{DC} = R_1 \cdot {I_{1N}}^2 + R_2 \cdot {I_{2N}}^2 = 0,15 \cdot 50^2 + 0,006 \cdot 250^2 = 750\,\mathrm{W}$$

Tilleggstapet er

$$P_{till} = P_b - P_{DC} = 900 - 750 = 150\,\mathrm{W}$$

c.
Belastningstapet ved 75 °C er

$$P_{b75} = P_{DC}\frac{235+75}{235+\vartheta} + P_{till}\frac{235+\vartheta}{235+75} = 750 \cdot \frac{235+75}{235+20} + 150 \cdot \frac{235+20}{235+75} = 1040\,\mathrm{W}$$

d.
Virkningsgraden ved halv last er

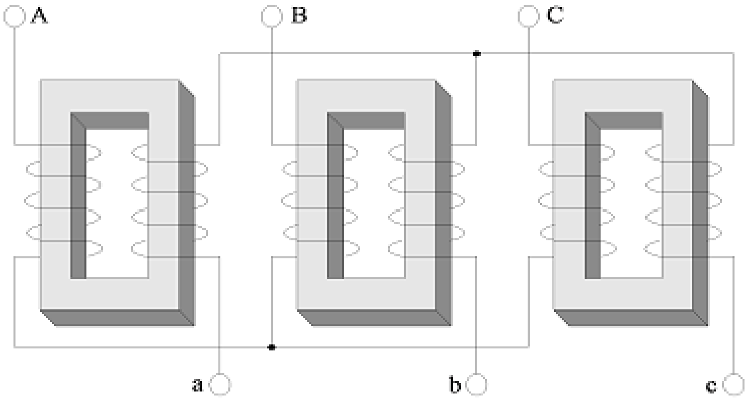
$$\eta_{50\%} = \frac{nS_N\cos\varphi_2}{nS_N\cos\varphi_2 + P_0 + n^2P_{b75}} = \frac{0,5 \cdot 50000 \cdot 0,8}{0,5 \cdot 50000 \cdot 0,8 + 400 + 0,5^2 \cdot 1040} = 96,8\%$$

Virkningsgraden ved full last er

$$\eta_{100\%} = \frac{nS_N\cos\varphi_2}{nS_N\cos\varphi_2 + P_0 + n^2P_{b75}} = \frac{1,0 \cdot 50000 \cdot 0,8}{1,0 \cdot 50000 \cdot 0,8 + 400 + 1,0^2 \cdot 1040} = 93,3\%$$

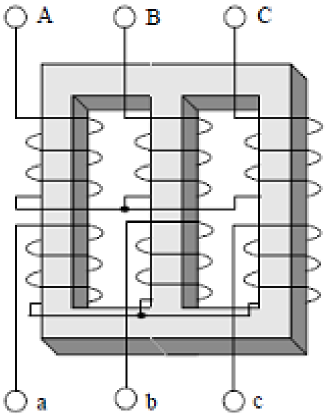
5.6 Trefasetransformatorer

Ved overføring av større effekter, lønner det seg å bruke trefasetransformatorer. Dette kan en løse ved å benytte tre stykk enfasetransformatorer, slik figur 5.13 viser.



Figur 5.13: Trefasekobling av tre stykk enfasetransformatorer

Dersom man i stedet plasserer viklingene på en felles kjerne, slik figur 5.14 viser, får man en mye mer kompakt trefasetransformator.



Figur 5.14: Trefasetransformator med viklinger på felles kjerne

Antall viklinger er det samme i begge tilfelle, og forholdet mellom vindingstallene N_1 og N_2 vil være det samme. Siden summen av fluksene i de tre kjernebeina alltid vil være null ved balanserte strømmer, vil den kompakte kjerna på figur 5.14 vanligvis være tilstrekkelig. Resultatet er en plassbesparende og billigere transformator.
Merkeeffekten for en trefasetransformator er gitt ved

$$S_N = \sqrt{3} U_{1N} I_{1N} \tag{5.45}$$

De relative spenningene e_r, e_x og e_z bruker nominell fasespenning på primærsiden som referansespenning. I en trefasetransformator vil en nemlig beregne spenningsfallene per fase. Dermed blir de relative spenningsfallene definert som

$$\begin{gathered} e_r = \sqrt{3} \cdot \tfrac{I_{1N} {R_k}'}{U_{1N}} 100\% \\ e_x = \sqrt{3} \cdot \tfrac{I_{1N} {X_k}'}{U_{1N}} 100\% \\ e_z = e_k = \sqrt{3} \cdot \tfrac{I_{1N} {Z_k}'}{U_{1N}} 100\% \end{gathered} \tag{5.46}$$

Eksempel 8 *En* 200 *kVA trefasetransformator med omsetningsforhold* $22000/240$ *V har følgende spenningsfall:* $e_r = 2,0\%$*,* $e_z = 5,5\%$*. Regn ut merkestrømmer og impedanskomponentene til kortslutningsimpedansen sett fra generatorsiden.*

Løsning:
Primær merkestrøm:

$$I_{1N} = \frac{S_N}{\sqrt{3} U_{1N}} = \frac{200000}{\sqrt{3} \cdot 22000} = 5,25\,\mathrm{A}$$

Sekundær merkestrøm:

$$I_{2N} = I_{1N} \cdot \frac{U_{1N}}{U_{2N}} = 5,25 \cdot \frac{22000}{240} = 481\,\mathrm{A}$$

Kortslutningsresistansen:

$${R_k}' = \frac{U_{1N}}{\sqrt{3} I_{1N}} e_r = \frac{22000}{\sqrt{3} \cdot 5,25} \cdot 0,02 = 48,4\,\Omega$$

Kortslutningsimpedansen:

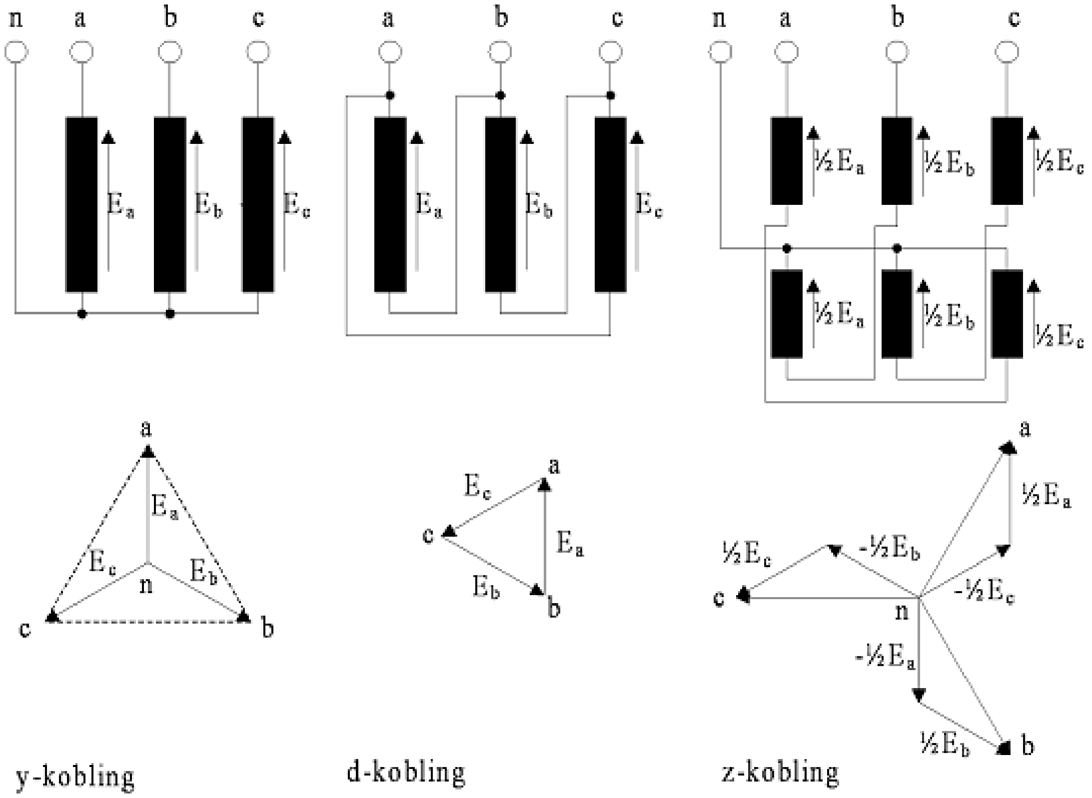
$${Z_k}' = \frac{U_{1N}}{\sqrt{3} I_{1N}} e_z = \frac{22000}{\sqrt{3} \cdot 5,25} \cdot 0,055 = 133\,\Omega$$

Kortslutningsreaktansen:

$${X_k}' = \sqrt{{Z_k}'^2 - {R_k}'^2} = \sqrt{133^2 - 48,4^2} = 123,9\,\Omega$$

5.7 Koblingsgrupper

Et sett trefaseviklinger kan kobles på tre måter, som vist på figur 5.15. I tillegg til vanlig stjernekobling (y-kobling) og trekantkobling (d-kobling), kan viklingene kobles i siksak (z-kobling). Sistnevnte koblingstype krever som det fremgår av figuren at viklingene er delte. Siksak-kobling brukes hovedsakelig i lavspente anlegg med n-leder hvor det er mye usymmetrisk last. Koblingsmåten skaper fluksbalanse i kjerna selv om linjestrømmene ikke er i balanse. Ved y- og z-kobling er nøytralpunktet tilkoblet en egen klemme merket n.



Figur 5.15: Trefasekoblinger

Forholdet mellom linje- og fasespenning er gitt i formel (5.47):

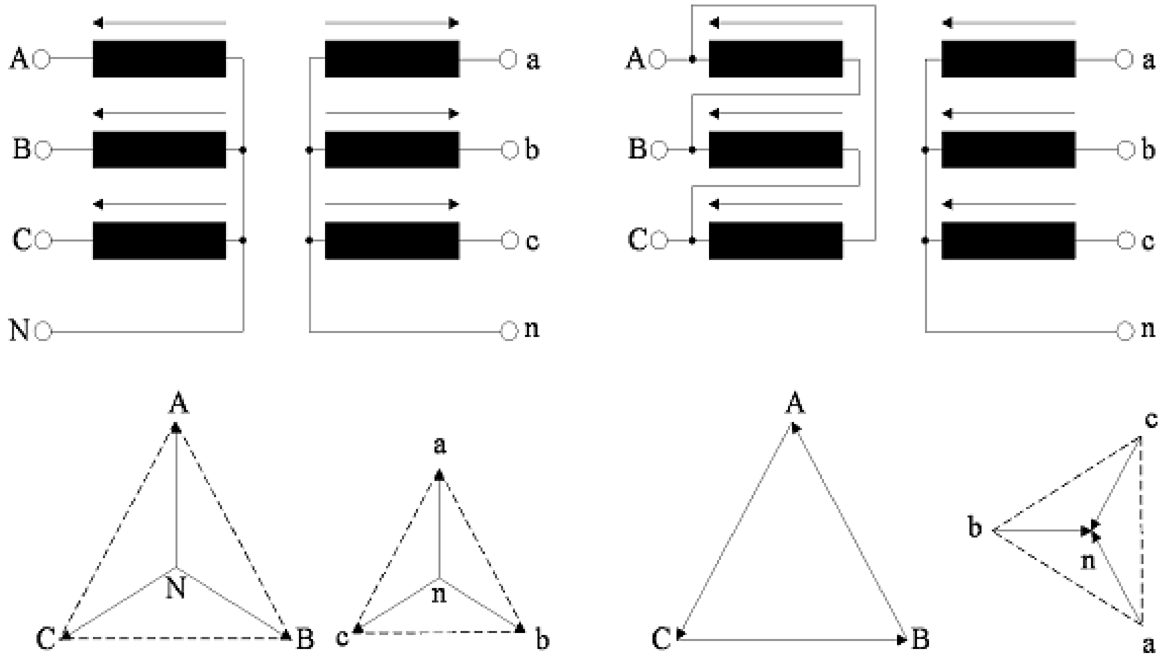
$$\begin{aligned}\frac{E}{E_f} &= \sqrt{3}\ \text{(y-kobling)}\\ \frac{E}{E_f} &= 1\ \text{(d-kobling)}\\ \frac{E}{E_f} &= 1,5\ \text{(z-kobling)}\end{aligned}\tag{5.47}$$

Det betyr at y-koblingen vil gi størst sekundærspenning for et gitt omsetningsforhold, og d-koblingen minst. Når det gjelder linjestrøm derimot, vil den ved d-kobling være roten av tre ganger høyere enn fasestrømmen, mens den for y- eller z-kobling vil være lik fasestrømmen.

5.8 Merking og klokketimetall

Siden både primær- og sekundærsiden kan kobles på en flere ulike måter, vil en trefasetransformator kunne kobles på svært mange måter. For å holde styr på dette uten å måtte åpne transformatoren eller lete frem dokumentasjon, er en trefasetransformator utstyrt med et merkeskilt som blant annet inneholder et koblingsgruppesymbol i henhold til gjeldende standard. Klemmene på den siden som har høyest spenningsnivå (oppsiden) merkes med store bokstaver (A, B, C og eventuelt N), mens de på den siden som har lavest spenningsnivå (nedsiden) merkes med små bokstaver (a, b, c og eventuelt n).

Første tegn i koblingsgruppesymbolet angir koblingsmåten på høyspentsiden og skrives med stor bokstav (Y, D eller Z). Dersom høyspentsiden har uttak for nøytralpunkt, følger en stor N. Deretter angis koblingsmåten på lavspentsiden med liten bokstav (y, d eller z). Hvis lavspentsiden har uttak for nøytralpunkt, kommer en påfølgende liten n. Det siste tegnet i koblingsgruppesymbolet er et tall, det såkalte klokketimetallet.
De ulike koblingsmåtene vil kunne gi forskjellig fasedreining mellom høyspent og lavspent linjespenning. Spenningene kan være i fase eller fasedreid 30°, 60° osv. Høyspent fasespenning i fase A velges som referanse og peker rett opp. Da vil lavspent fasespenning i fase a peke i en vinkel som er et multiplum av 30°, altså som timeviseren på ei urskive. Dersom høyspent og lavspent fasespenning peker i samme retning (rett opp), tilsvarer det klokka tolv. Det tilsvarer klokketimetall 0. Dersom lavspent fasespenning ligger 150° etter, peker den mot klokka fem, og det gir klokketimetall 5. Figur 5.16 illustrerer dette.



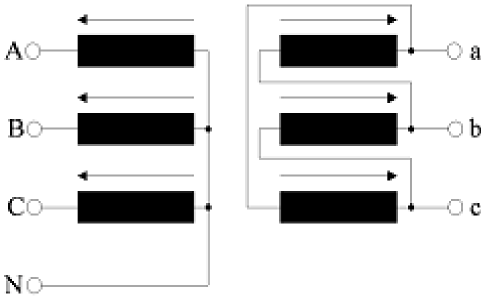
(a) YNyn0

(b) Dyn5

Figur 5.16: Trefasekoblinger med koblingsgruppesymboler

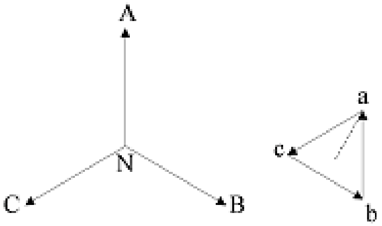
Dersom en trefasetransformator er merket Dyn11, betyr det at høyspentviklingen er d-koblet, at lavspentviklingen er y-koblet med nøytralpunktuttak og at spenningene er 330° fasedreid.

Eksempel 9 *Bestem koblingsgruppesymbolet for transformatoren på figur 5.17.*



Figur 5.17: Trefasetransformator

Løsning:
Høyspentsiden er Y-koblet, med uttak for nullpunkt, og dette angis med YN. Lavspentsiden er D-koblet, og dette angis med d. Figur 5.18 viser hvordan spolespenningene på høyspent- og lavspentsiden peker i samme retning for hvert kjernebein. Siden lavspentsiden er d-koblet, vil fasespenningen gå ut fra et tenkt nullpunkt (stiplet linje). Denne linja peker mot klokka 1. Altså er koblingsgruppesymbolet YNd1.

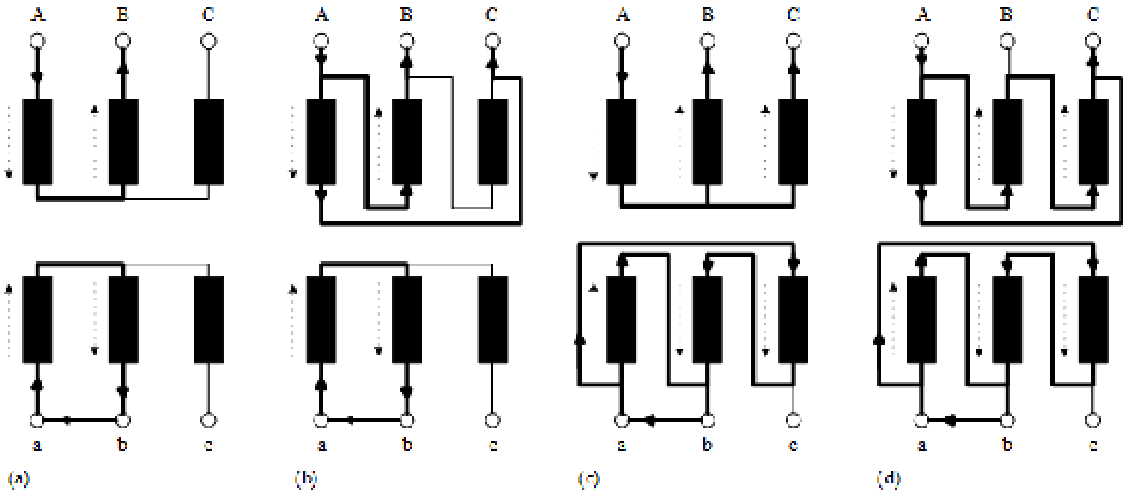


Figur 5.18: Spenningsvisere på høyspent- og lavspentsiden

5.9 Usymmetriske feilsituasjoner

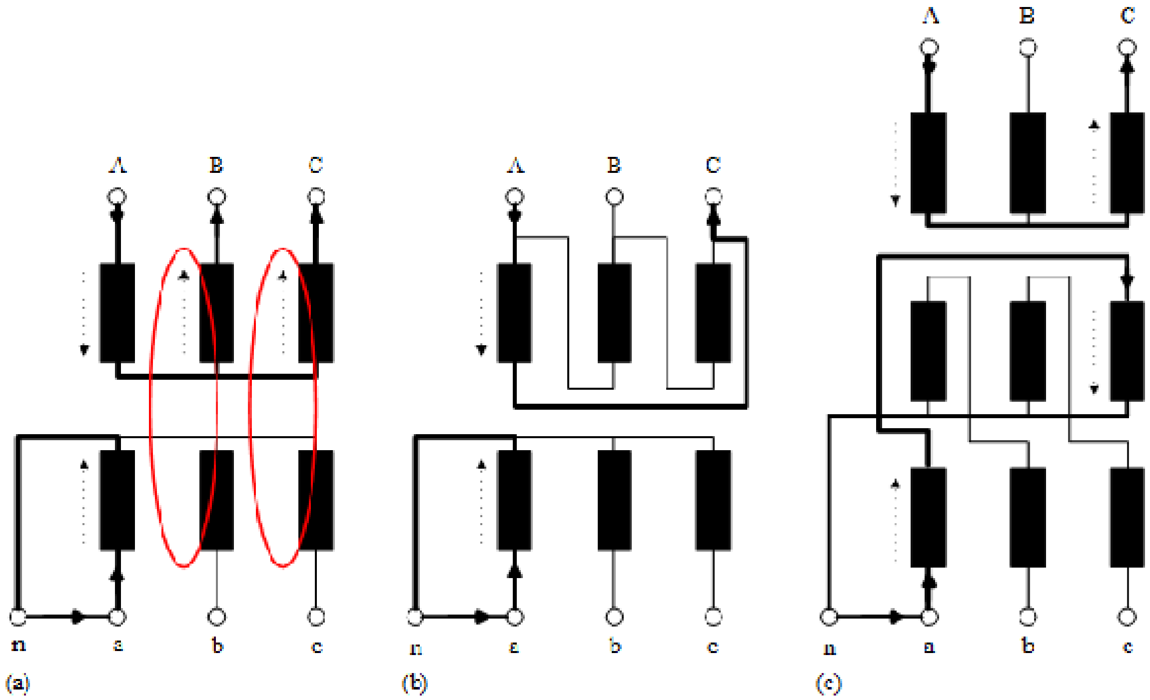
Dersom det inntreffer kortslutning, jordslutning eller betydelig skjevlast på sekundærsiden av en trefasetransformator, kan det skape ugunstige fluksforhold i kjerna. I prinsipp skjer det samme ved kortslutning/jordslutning som ved skjevlast, bare i mye større grad. Derfor vil påfølgende analyse kun ta for seg usymmetriske kortslutninger og jordslutninger.

De uthevede linjene på figur 5.19 og 5.20 viser kortslutnings- eller jordslutningsstrømmer, mens de stiplede linjene angir retningen på den magnetomotoriske kraft fra hver vikling. En ser av figur 5.19 at det vil være amperevindingsbalanse (primær og sekundær mmk utligner hverandre) ved tofase kortslutning, uansett koblingsmåte ($I_1 N_1 = I_2 N_2$). Størrelsen på kortslutningsstrømmene vil imidlertid være avhengig av hvilken kobling som velges.



Figur 5.19: Tofase kortslutning for ulike transformatorkoblinger

Dersom det skjer en enfase jordslutning i et TN-nett, vil noen koblingsmåter gi amperevindingsbalanse, andre ikke.



Figur 5.20: Enfase jordslutning for ulike transformatorkoblinger

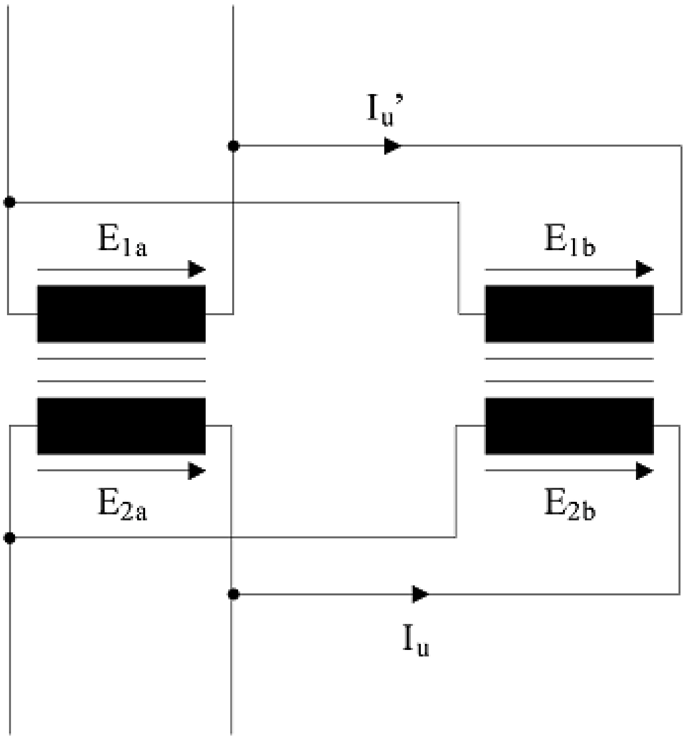
På figur 5.20a inntreffer en enfase jordslutning mellom fase a og n. Strømmen på primærsiden i fase A finner tilbakevei gjennom fase B og C og skaper dermed mmk gjennom de respektive kjernebeina. Resultatet er at det ikke er amperevindingsbalanse. Det oppstår et luftfelt mellom toppen og bunnen av kjerna, et såkalt åkfelt, og dette induserer virvelstrømmer i transformatorkassen og andre metalldeler. Velger man derimot Dy-kobling som vist på figur 5.20b, unngår man problemet, da strømmen på primærsiden har en returvei over klemme C. Et annet alternativ er Yz-kobling, vist på figur 5.20c. Z-koblingen gjør at feilstrømmen fordeler seg likt på to kjernebein, og i motsatt retning. Dermed kan strømmen på primærsiden gå gjennom to faser, og det oppnås amperevindingsbalanse.

5.10 Parallelldrift

Noen ganger ønsker en å parallellkoble to transformatorer, enten for å øke overføringskapasiteten eller for å ha reservekapasitet dersom en av transformatorene skulle svikte.
Tre betingelser må være oppfylt for at transformatorene skal kunne parallellkobles:

1. De må ha samme klokketimetall
2. De må ha samme spenningsomsetning i tomgang
3. De må ha omtrent samme relative kortslutningsspenning e_k.

Dersom man parallellkobler to transformatorer og den første betingelsen ikke er oppfylt, vil spenningene på sekundærsiden være fasedreid selv om primærspenningene er i fase. En fasedreining på 30° eller mer vil skape meget kraftige sirkulasjonsstrømmer mellom sekundærkretsene på de to transformatorene.
Dersom transformatorene ikke har samme spenningsomsetning i tomgang, vil det flyte en utjevningsstrøm mellom dem. Det tilsvarer at man kobler sammen to spenningskilder med ulik utgangsspenning, som det fremgår av figur 5.21. Den resulterende utjevningsstrømmen drives av forskjellen i tomgangsspenning og begrenses av kortslutningsimpedansene, som angitt i formel 5.48. Det er verdt å merke seg at denne utjevningsstrømmen vil være en tilleggsbelastning for den transformatoren som har høyest tomgangsspenning, mens den vil virke i motsatt retning av laststrømmen for den andre transformatoren.



Figur 5.21: Parallellkoblede transformatorer

$$\begin{aligned}\text{enfase: } I_u &\approx \frac{U_{2A}-U_{2B}}{Z_{kA}''+Z_{kB}''}\\ \text{trefase: } I_u &\approx \frac{U_{2A}-U_{2B}}{\sqrt{3}(Z_{kA}''+Z_{kB}'')}\end{aligned} \tag{5.48}$$

Dersom transformatorene har forskjellig relativ kortslutningsspenning, vil de ikke dele belastningen i forhold til merkeeffektene. Den transformatoren som har høyest relative kortslutningsspenning (og dermed høyest impedans) vil føre mindre strøm.
Hvis transformator a og b har samme kortsutningspenning, kan en skrive

$$\begin{aligned}\text{enfase: } e_k &= \tfrac{Z_{ka}{}' I_{aN}}{U_{1N}} = \tfrac{Z_{kb}{}' I_{bN}}{U_{1N}} \\ \text{trefase: } e_k &= \sqrt{3}\tfrac{Z_{ka}{}' I_{aN}}{U_{1N}} = \sqrt{3}\tfrac{Z_{kb}{}' I_{bN}}{U_{1N}}\end{aligned} \tag{5.49}$$

Dette gir at

$$\frac{Z_{ka}{}'}{Z_{kb}{}'} = \frac{I_{bN}}{I_{aN}} \tag{5.50}$$

og siden de har samme merkespenning U_{1N}, kan vi også sette at

$$\frac{S_{bN}}{S_{aN}} = \frac{I_{bN}}{I_{aN}} \tag{5.51}$$

som tilsier at dersom transformatorene har samme relative kortslutningsspenning, vil den transformatoren som har størst merkeeffekt, også føre størst laststrøm.

Eksempel 10 *To parallellkoblede trefasetransformatorer mates fra et* $22\,\mathrm{kV}$ *nett og forsyner et* $400\,\mathrm{V}$ *lavspentnett. Trafo A har spenningsomsetning i tomgang:* $22000/400\,\mathrm{V}$*, merkeeffekt* $500\,\mathrm{kV\,A}$ *og kortslutningsspenningsfall* $e_k = 6,0\%$*. Trafo B har spenningsomsetning i tomgang:* $22500/400\,\mathrm{V}$*, merkeeffekt* $300\,\mathrm{kV\,A}$ *og kortslutningsspenningsfall* $e_k = 5,5\%$*. Beregn utjevningsstrømmen og laststrømmen på sekundærsiden av hver trafo ved full last hvis laststrømmen har* $\varphi = 30\,^\circ$ *og begge impedansene har en fasevinkel på* $75\,^\circ$*.*

Løsning:
Trafo A har $400\,\mathrm{V}$ på sekundærsiden i tomgang: Trafo B har følgende sekundærspenning:

$$U_{2B} = 22000 \cdot \frac{400}{22500} = 391\,\mathrm{V}$$

Ser vi bort fra spenningsfallet under belastning, har trafoene følgende sekundære merkestrømmer:

$$\begin{aligned}I_{2a,N} &= \tfrac{S_{aN}}{\sqrt{3}U_{2a,N}} = \tfrac{500000}{\sqrt{3}\cdot 400} = 722\,\mathrm{A} \\ I_{2b,N} &= \tfrac{S_{bN}}{\sqrt{3}U_{2b,N}} = \tfrac{300000}{\sqrt{3}\cdot 400} = 433\,\mathrm{A}\end{aligned}$$

Kortslutningsimpedansene sett fra sekundærsiden er:

$$\begin{aligned}Z''_{ka} &= e_{ka}\tfrac{U_{2a,N}}{\sqrt{3}I_{2a,N}} = 0,06 \cdot \tfrac{400}{\sqrt{3}\cdot 722} = 19,2\,\mathrm{m\Omega} \\ Z''_{kb} &= e_{kb}\tfrac{U_{1b,N}}{\sqrt{3}I_{2b,N}} = 0,055 \cdot \tfrac{400}{\sqrt{3}\cdot 433} = 29,3\,\mathrm{m\Omega}\end{aligned}$$

Utjevningsstrømmen blir tilnærmet lik:

$$I_u \approx \frac{U_{2A} - U_{2B}}{\sqrt{3}\,(Z_{kA}{}'' + Z_{kB}{}'')} = \frac{400 - 391}{\sqrt{3} \cdot (0,0192 + 0,0293)} = 107\,\mathrm{A}$$

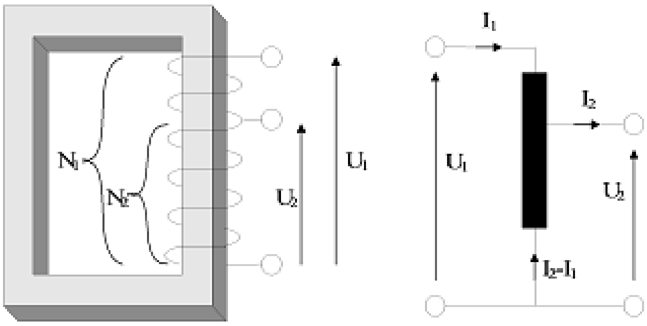
Som det fremgår av figur 5.21, vil utjevningsstrømmen flyte i samme retning som laststrømmen i trafo A, og i motsatt retning av laststrømmen i trafo B. De resulterende laststrømmene blir derfor:

$$\begin{aligned}I_{2a} &= I_{2a,N} + I_u = 722\angle -30\,^\circ + 107\angle -75\,^\circ = 810\,\mathrm{A}\angle -35,4\,^\circ \\ I_{2b} &= I_{2b,N} - I_u = 433\angle -30\,^\circ - 107\angle -75\,^\circ = 365\,\mathrm{A}\angle -18,0\,^\circ\end{aligned}$$

5.11 Spesielle transformatortyper

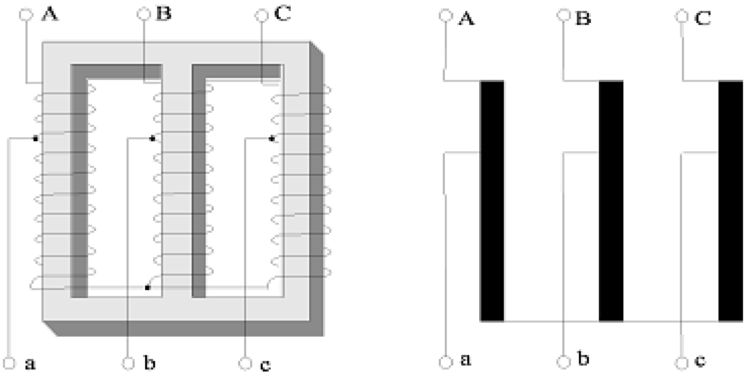
Autotransformator

Autotransformatorer er transformatorer hvor primær- og sekundærkretsen er plassert på en felles vikling, som vist på figur 5.22. Indusert spenning er proporsjonal med vindingstallet, og derfor vil spenningen over U_1 være høyere enn over U_2 på figuren. Viklingen består av en fellesdel og en seriedel . Det fremgår av figuren at strømmen i fellesdelen utgjør differansen mellom I_2 og I_1, og derfor kan ledertverrsnittet reduseres i denne delen av viklingen.
En autotransformator er altså en mer kompakt løsning enn en toviklingstransformator. Den største ulempen med en autotransformator er imidlertid at den ikke gir galvanisk skille mellom primær- og sekundærsiden.



Figur 5.22: Prinsipp og koblingsskjema for enfase autotransformator

Autotransformatoren finnes også i trefaseutførelse og er da koblet i stjerne, som vist på figur 5.23.



Figur 5.23: Prinsipp og koblingsskjema for trefase autotransformator

For en ideell autotransformator gjelder

$$\frac{U_1}{U_2} = \frac{I_2}{I_1} = \frac{N_1}{N_2} \tag{5.52}$$

For autotransformatorer må en skille mellom den tilsynelatende effekten som overføres gjennom transformatoren (gjennomgangseffekten) og den effekten som overføres ved magnetisk kobling (egeneffekten eller typeeffekten). Gjennomgangseffekten blir

$$\begin{aligned} S_g &= U_{1N} I_{1N} = U_{2N} I_{2N} && \text{(enfase)} \\ S_g &= \sqrt{3} U_{1N} I_{1N} = \sqrt{3} U_{2N} I_{2N} && \text{(trefase)} \end{aligned} \tag{5.53}$$

Egeneffekten er den tilsynelatende effekt i hver del av viklingen. For en nedtransformerende autotransformator er denne gitt ved:

$$\begin{aligned} S_e &= (U_{1N} - U_{2N})\, I_{1N} = U_{2N}\,(I_{2N} - I_{1N}) && \text{(enfase)} \\ S_e &= \sqrt{3}\,(U_{1N} - U_{2N})\, I_{1N} = \sqrt{3} U_{2N}\,(I_{2N} - I_{1N}) && \text{(trefase)} \end{aligned} \tag{5.54}$$

Eksempel 11 *Beregn egeneffekten for en 1,0 kVA enfase autotransformator med spenningsomsetning 1000/200 V.*

Løsning:
Primær merkestrøm er

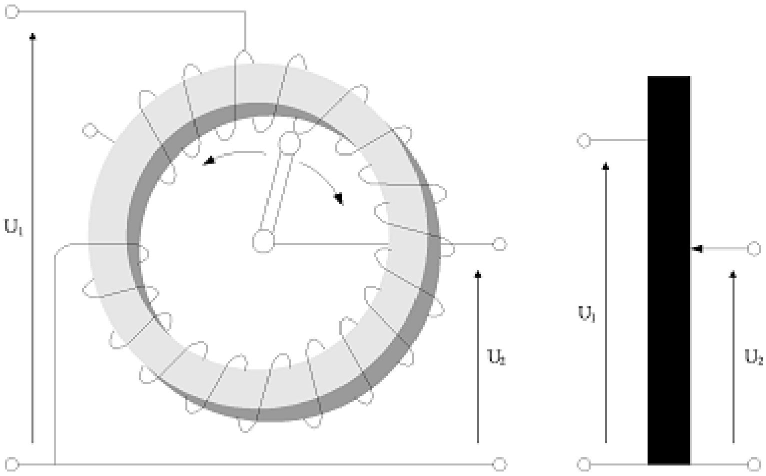
$$I_{1N} = \frac{S_g}{U_{1N}} = \frac{1000}{1000} = 1,0\,\mathrm{A}$$

Egeneffekten er

$$S_e = (U_{1N} - U_{2N})\, I_{1N} = (1000 - 200) \cdot 1,0 = 800\,\mathrm{V\,A}$$

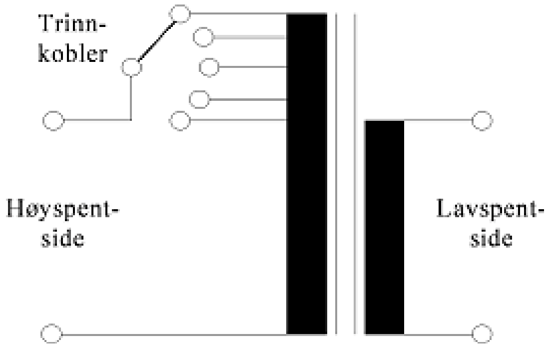
Regulertransformatorer

Regulertransformatorer for små effekter bygges opp som vist på figur 5.24. Dette er en autotransformator med variabelt vindingstall på sekundærsiden. En løser dette ved å benytte en glidekontakt, som vist på figuren. Denne transformatortypen brukes mye til laboratorieformål og finnes både i enfase- og trefaseutførelser. Transformatoren kalles gjerne en variac.



Figur 5.24: Prinsipp og koblingsskjema for enfase regulertransformator med glidekontakt, en såkalt variac

I kraftnettet er det behov for å endre omsetningsforholdet for å holde nettspenningen konstant. Dette oppnås ved å endre vindingstallet på høyspentsiden . Høyspentviklingen er da utstyrt med en rekke uttak og mulighet for omkobling mellom disse. På fordelingstransformatorer skjer omkoblingen når transformatoren er spenningsløs. Store krafttransformatorer er derimot utstyrt med såkalte trinnkoblere som gjør at de kan endre omsetningsforholdet under drift. Figur 5.25 viser en prinsippskisse av en transformator med trinnkobler.

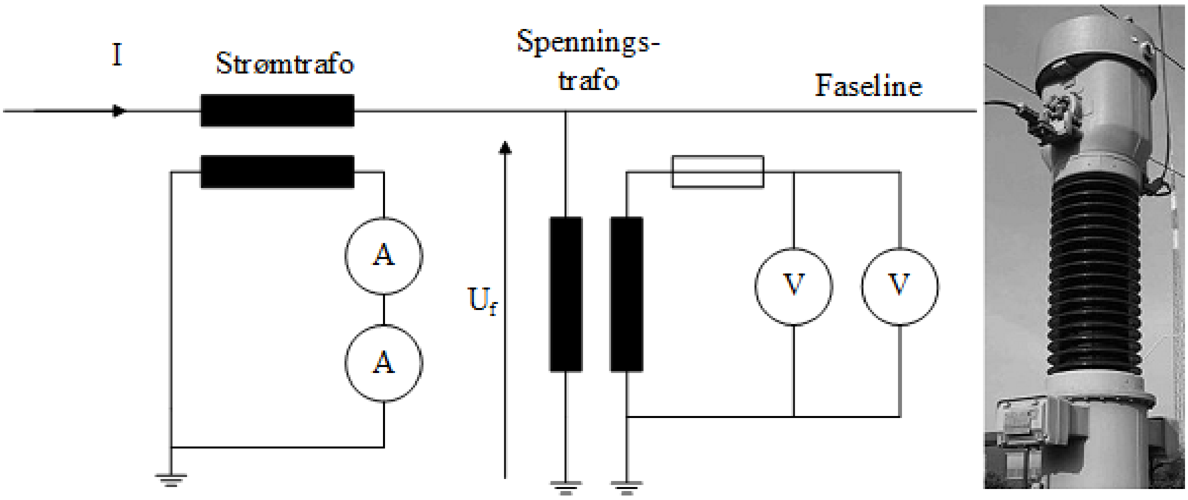


Figur 5.25: Regulertransformator med trinnkobler

Måletransformatorer

Måletransformatorer brukes i kretser med svært høye spenninger og/eller strømmer, hvor utstyr for direkte måling vil være svært dyrt og risikabelt å benytte. Dette gjelder ikke minst for målinger i høyspentnettet. Strømtransformatorer fører målestrømmen (linjestrømmen) i primærkretsen (koblet som et amperemeter) og har et omsetningsforhold slik at N_2 er større enn N_1. Dermed transformeres strømmen ned til en verdi som egner seg for måleinstrumenter. Spenningstransformatorer fører målespenningen (som regel fasespenningen) i primærkretsen (koblet som et voltmeter) og har et omsetningsforhold slik at N_1 er større enn N_2. Dermed transformeres spenningen ned til en verdi som egner seg for måleinstrumenter. Måletransformatorer kobles ikke bare til måleutstyr, men også til utstyr for styring og vern (releer m.m.).

Figur 5.26 viser oppkobling av strømtransformator og spenningstransformator (til venstre). Til høyre er et bilde av en strømtransformator på 110kV nettet.

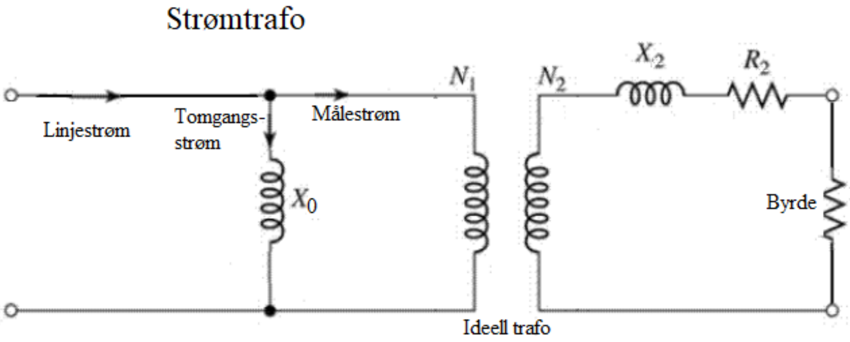


Figur 5.26: Oppkobling av strømtransformator og spenningstransformator (venstre). Bilde av en strømtransformator for 110 kV-nettet (til høyre)

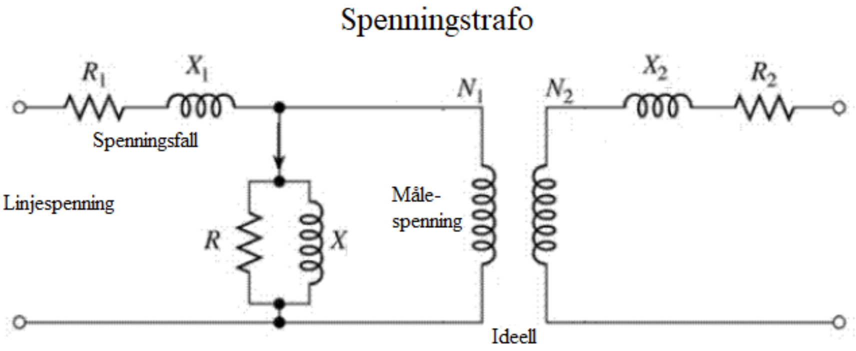
Følgende betingelser må være oppfylt ved bruk av måletransformatorer:

1. Dersom en trenger mer enn ett instrument i sekundærkretsen, må strømtransformatoren ha dem i serie, mens spenningstransformatoren må ha dem i parallell.
2. Strømtransformatorer skal ha lavohmig sekundærkrets (tilnærmet kortslutning), mens spenningstransformatorer skal ha høyohmig sekundærkrets (tilnærmet åpen krets).
3. Måletransformatorer som kobles til et høyspent primærnett skal ha den ene enden av sekundærviklingen jordet for å sikre at en ikke får høyspenning i sekundærkretsen ved isolasjonsfeil.

4. Strømtransformatorer må aldri vernes med sikringer, mens spenningstransformatorer alltid må vernes med sikringer!



Figur 5.27: Ekvivalentskjema for strømtrafo



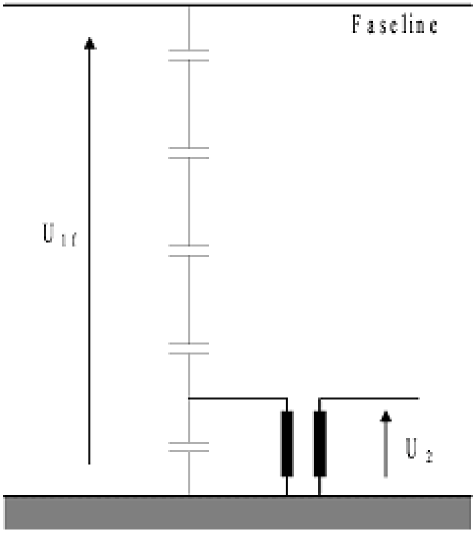
Figur 5.28: Ekvivalentskjema for spenningstrafo

For strømtransformatorer vil det alltid være en liten omsetningsfeil i og med at tomgangsstrømmen I_0 kommer i tillegg til målestrømmen, som det fremgår av figur 5.27. For spenningstransformatorer vil det være en omsetningsfeil på grunn av spenningsfallet i primærviklingen, grunnet tomgangsstrømmen. Dette er illustrert i figur 5.28. Det gjelder derfor å minimere disse feilene, som for øvrig også er opphav til en liten vinkelfeil. Måletransformatorer er inndelt i nøyaktighetsklasser som angir målefeilen i prosent. Tabell 5.1 viser disse klassene.

Tabell 5.1: Nøyaktighetsklasser og anvendelsesområder for måletransformatorer

Klasse	Anvendelsesområde
0,1	Presisjonsmåling (i laboratorier)
0,2	Presisjonsmåling og nøyaktig avregning av energi
0,5	Nøyaktig måling av strøm og spenning
0,5	Vanlig energiavregning
1,0	Tavleinstrumenter
3,0	Indikerende instrumenter. Releer

Ved svært høye spenninger (over 100 kV) lønner det seg ikke å bygge vanlige spenningstransformatorer. En bruker da kapasitive spenningsdelere, som vist på figur 5.29. Transformatoren måler da bare en del av den totale fasespenningen. Slike kapasitive spenningsdelere vil i tillegg være med på å filtrere bort høyfrekvent signaloverføring langs høyspentlinjene.



Figur 5.29: Spenningstransformator med kapasitiv spenningsdeler

Eksempel 12 *En strømtrafo har omsetningsforhold* $500/5\,\mathrm{A}$. *Sekundær impedans er* $R_2 = 0,2\,\Omega$ *og* $X_2 = 1,0\,\Omega$. *Målekretsen har en byrde* $R_L = 0,5\,\Omega$. *Trafoen har en tomgangsreaktans* $X_0 = 2,0\,\Omega$. *Beregn ideell og virkelig målestrøm ved en linjestrøm på* $392\,\mathrm{A}$.

Løsning:
Total impedans sett fra primærsiden:

$$\overrightarrow{Z}'_k = \left(\frac{I_{2N}}{I_{1N}}\right)^2 (R_2 + R_L + jX_2) = \left(\frac{5}{500}\right) \cdot (0,2 + 0,5 + j1,0) = 0,0122\,\Omega\angle 55\,^\circ$$

Primær klemmespenning har følgende verdi

$$\overrightarrow{U}_1 = \overrightarrow{I}_1 \cdot \overrightarrow{Z}'_k = 392 \cdot 0,0122\angle 55\,^\circ = 4,78\,\mathrm{V}\angle 55\,^\circ$$

Tomgangsstrømmen blir da

$$I_0 = \frac{\overrightarrow{U}_1}{jX_0} = \frac{4,78\angle 55\,^\circ}{j2} = 2,39\,\mathrm{A}\angle -35\,^\circ$$

Ideell målestrøm er

$$I_2 = 392 \cdot \frac{5}{500} = 3,92\,\mathrm{A}$$

Virkelig målestrøm er

$$I_2 = (392 - 2,39\angle -35\,^\circ) \cdot \frac{5}{500} = 3,9\,\mathrm{A}\angle -35\,^\circ$$

Avviket er

$$\frac{392 - 390}{392} = 0,5\%$$

Eksempel 13 *En spenningstrafo har omsetningsforhold* $12700/220\,\mathrm{V}$. *Primær impedans er* $R_1 = 10\,\Omega$ *og* $X_1 = 45\,\Omega$. *Trafoen har en tomgangsreaktans* $X_0 = 1,0\,\mathrm{k}\Omega$. *Beregn ideell og virkelig målespenning ved en nettspenning på* $12\,\mathrm{kV}$.

Løsning:
Tomgangsstrøm:

$$\overrightarrow{I}_0 = \frac{\overrightarrow{U}_1}{jX_0} = \frac{12000}{j1000} = 12\,\mathrm{A}\angle-90\,^\circ$$

Primært spenningsfall:

$$\overrightarrow{\Delta U} = \overrightarrow{I}_0\,(R_1 + jX_1) = 12\angle-90\,^\circ \cdot (10 + j45) = 553\,\mathrm{V}\angle-12,5\,^\circ$$

Ideell målespenning:

$$U_2 = 12000 \cdot \frac{220}{12700} = 208\,\mathrm{V}$$

Virkelig målespenning:

$$U_2 = (12000 - 553\angle-12.5\,^\circ) \cdot \frac{220}{12700} = 199\,\mathrm{V}\angle 0,6\,^\circ$$

Avviket er

$$\frac{208 - 199}{208} = 4,3\%$$

Eksempel 14 *En kapasitiv spenningdeler har en øvre kapasitans* $C_1 = 200\,\mathrm{nF}$ *og en nedre kapasitans* $C_2 = 800\,\mathrm{nF}$. *Nominell primærspenning er* $240\,\mathrm{kV}$, *og spenningstrafoen har et omsetningsforhold på 435/1. Nettfrekvensen er* $50\,\mathrm{Hz}$. *Hva blir nominell utgangsspenning?*

Løsning:
Spenningedeleren har følgende reaktanser:

$$\begin{array}{c} X_1 = \frac{1}{2\pi f C_1} = \frac{1}{2\pi\cdot 50\cdot 200\cdot 10^{-9}} = 15,9\,\mathrm{k}\Omega \\ X_2 = \frac{1}{2\pi f C_2} = \frac{1}{2\pi\cdot 50\cdot 800\cdot 10^{-9}} = 3,8\,\mathrm{k}\Omega \end{array}$$

Spenningen ut av spenningsdeleren blir

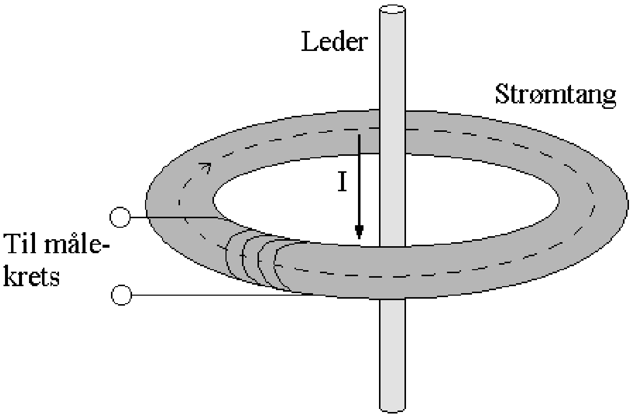
$$U_1 = U_{nett} \cdot \frac{X_2}{X_1 + X_2} = 240 \cdot \frac{3,8}{15,9 + 3,8} = 46,3\,\mathrm{kV}$$

Utgangsspenningen blir

$$U_2 = 46300 \cdot \frac{1}{435} = 106\,\mathrm{V}$$

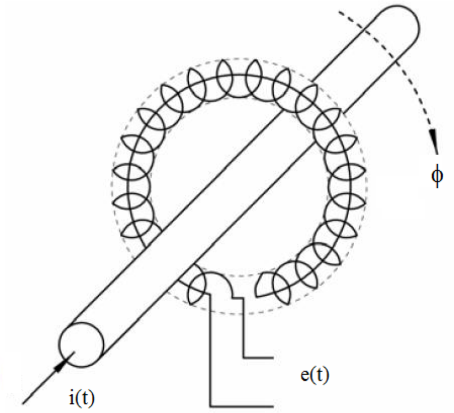
Strømtang, strømslange

På lavspentanlegg kan man også benytte såkalte tang-amperemeter for å måle strømmen i en leder. Virkemåten er vist på figur 5.30. Når tanga lukkes, sluttes en magnetisk krets rundt lederen. Primært vindingstall vil alltid være 1, og sekundært vindingstall bestemmer hvor mye strømmen skal nedtransformeres.



Figur 5.30: Virkemåte for tang-amperemeter (strømtang)

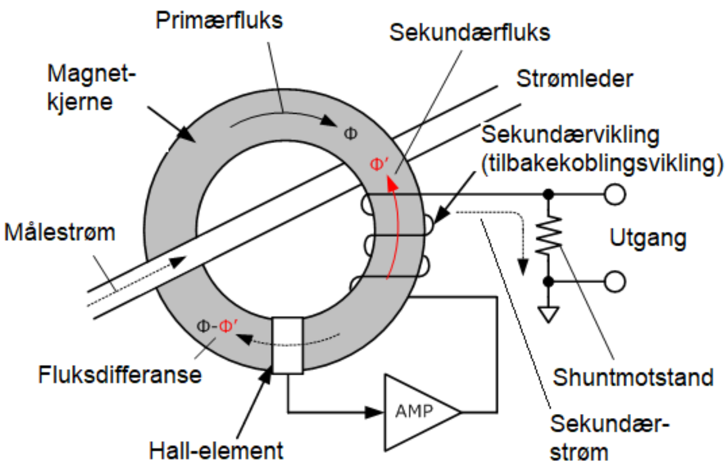
Ved svært høye strømmer kan det være hensiktsmessig å benytte en såkalt Rogowski-spole, også kalt strømslange, som vist på figur 5.31. Fluksen rundt lederen induserer en spenning i spolen, som det fremgår av formel 5.55. Hvis man integrerer denne ligningen med hensyn på tiden, finner man et uttrykk for fluksen rundt lederen. For Rogowski-spolen er $N = 1$. Siden fluksen og strømmen er proporsjonale, vil strømmen gjennom lederen være gitt ved formel 5.56. Legg merke til at returlederen i midten er helt sirkelformet, og det vil ikke induseres spenninger i denne. Lederen bør være sentrert og mest mulig vinkelrett på Rogowski-spolen for å oppnå mest mulig nøyaktig måling.



Figur 5.31: Virkemåte for Rogowski-spole

$$e = N\frac{d\phi}{dt} \tag{5.55}$$

$$i = k \cdot \phi = k \int e \cdot dt \tag{5.56}$$



Figur 5.32: Prinsippskisse for nullflukselement

Nullflukselement

Figur 5.32 viser ei prinsippskisse for et nullflukselement. Målestrømmen I_1 gjennom strømlederen skaper en primærfluks ϕ i kjerna. Sekundærstrømmen I_2 genererer en motfluks ϕ'. Hall-elementet måler fluksdifferansen $\phi - \phi'$. Dersom $\phi - \phi' > 0$, økes sekundærstrømmen I_2 inntil $\phi = \phi'$. Tilsvarende reduseres sekundærstrømmen dersom $\phi - \phi' < 0$. Når $\phi = \phi'$, er det ingen fluks i kjerna. Forholdet mellom primær- og sekundærestrømmen er da

$$I_1 = NI_2 \tag{5.57}$$

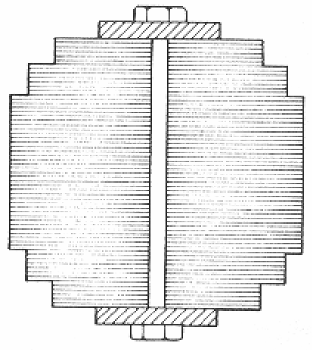
hvor N er antall tørn i sekundærspolen.
Dersom en ønsker å omforme målestrømmen til ei utgangsspenning, lar man sekundærstrømmen gå gjennom ei shuntmotstand R. Forholdet mellom målestrømmen I_1 og utgangsspenninga U_2 er da

$$U_2 = RI_2 = \frac{R}{N} I_1 \tag{5.58}$$

Nullflukselementet måler både like- og vekselstrømmer med stor presisjon så lenge primærstrømmen ikke overskrider $NI_{2,\max}$. Frekvensområdet begrenses av stigetida til sekundærstrømmen.

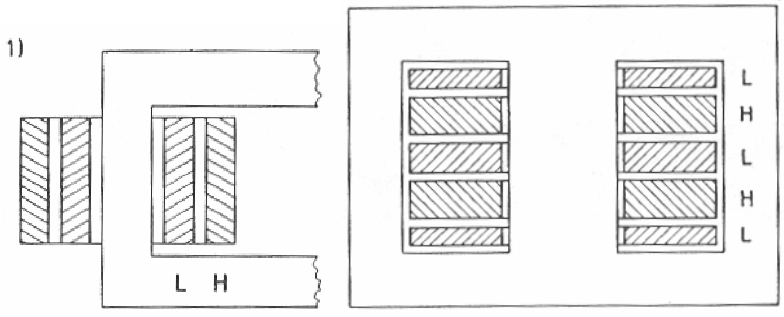
5.12 Oppbygning og hjelpeutstyr

Kjernen på en krafttransformator bygges opp slik at tverrsnittet blir mest mulig sirkelformet, slik det er vist på figur 5.33. Derved reduseres lekkfluksen i viklingene.



Figur 5.33: Tverrsnitt av kjernebein i krafttransformator

Vanligvis legges lavspentviklingen innerst mot kjernebeinet, og høyspentviklingen utenpå, slik det er vist til venstre på figur 5.34. Dette kalles sylingerviklinger. I en manteltransformator legges bladete viklinger oppå hverandre med lavspent- og høyspentviklinger vekselvis. Viklingene består som regel av aluminums- eller kobberledere og er ofte papirisolert. Transformatoren er senket ned i et oljebad som både gir isolasjon og kjøling.



Figur 5.34: Ulike måter å legge viklingene rundt kjernen

Figur 5.35 viser en gjennomskåret trefasetransformator. På toppen står en ekspansjonsbeholder (konservator) for transformatoroljen. På toppen av kassen ser en også gjennomføringer for høyspent- og lavspenttilkoblinger. Disse er forbundet med selve viklingene som er lagt rundt kjernebeina. På grunn av varmeutviklingen vil oljen sirkulere rundt i beholderen og transportere tapsvarme fra kjernen og viklingene ut mot transformatorkassen. Denne er utstyrt med utvendige kjøleribber for å gi best mulig varmetransport mot omgivelsene.

Figur 5.35: Gjennomskåret trefasetransformator

Store transformatorer er gjerne utstyrt med pumper som øker oljesirkulasjonen, samt vifter som øker luftstrømmen over kjøleribbene. Store transformatorer har også gjerne verneutstyr (en såkalt gassvakt) som registrerer gassutvikling i forbindelse med varmgang eller lysbuedannelse i transformatoroljen. For å unngå at kondens slipper inn, er oljebeholderen ofte utstyrt med et tørkeapparat. Noen moderne fordelingstransformatorer er helt innkapslet og har ingen oljebeholder.

5.13 Kjøling

Kjølemåten er angitt med en bokstavkode. Kjølemediet er angitt med enten A (luftkjøling), O (oljekjøling) eller W (vannkjøling). Sirkulasjonsmåten for kjølemidlet er enten N (naturlig) eller F (tvunget). Tørrisolerte transformatorer har kun ytre et ytre kretsløp med luftkjøling, mens oljefylte transformatorer har både et indre og et ytre kretsløp.

Selvkjølt tørrisolert transformator (AN)
Transformatoren avkjøles av sirkulerende luft gjennom naturlig konveksjon. Denne metoden er også kjent som en selvkjølt metode. Metoden brukes til å avkjøle mindre transformatorer opp til 1,5 MVA.

Tørrisolert transformator med tvungen kjøling (AF)
Transformatoren avkjøles av sirkulerende luft gjennom tvungen sirkulasjon ved bruk av vifter. Dersom temperaturen inni transformatoren overskrider tillatt nivå, aktiveres viftene automatisk. Denne metoden brukes til transformatorer opp til 15MVA.

Selvkjølt oljefylt transformator (ONAN)
Oljen sirkulerer inni transformatoren på grunn av naturlig konveksjon. Luften sirkulerer rundt transformatoren på grunn av naturlig konveksjon. Denne typen kjøling brukes til transformatorer opp til 30 MVA.

Oljefylt transformator med tvungen luftsirkulasjon (ONAF)
Oljen sirkulerer inni transformatoren på grunn av naturlig konveksjon. Omgivelsesluften blåses inn mot oljefylte radiatorer ved hjelp av vifter. Denne typen kjøling brukes til transformatorer opp til 60 MVA.

Oljefylt transformator med tvungen olje- og luftsirkulasjon (OFAF)
Oljen pumpes gjennom en varmeveksler som avkjøles av vifter. Omgivelsesluften blåses inn mot oljefylte radiatorer ved hjelp av vifter. Denne typen kjøling brukes til transformatorer opp til 60 MVA.

Oljefylt transformator med naturlig oljesirkulasjon og vannkjøling (ONWF)
Oljen sirkulerer naturlig gjennom en vannkjølt varmeveksler.

Oljefylt transformator med tvungen oljesirkulasjon og vannkjøling (ONWF)
Oljen pumpes gjennom en vannkjølt varmeveksler. Oljetrykket er høyere enn vanntrykket, for å unngå at vann trenger inn i oljen. Metoden brukes for transformatorer på flere hundre MVA.

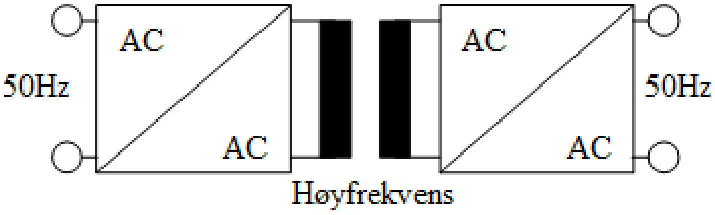
5.14 Elektroniske transformatorer

I følge transformatorligningen er fluks og frekvens omvendt proporsjonale størrelser dersom spenningen er konstant:

$$\begin{gathered} E = 4,44 \cdot N \cdot f \cdot \phi_{\max} \\ f \cdot \phi_{\max} = k \end{gathered} \tag{5.59}$$

Ved å påtrykke transformatoren en høyere sinusformet spenning enn 50 Hz, vil fluksen avta tilsvarende. Hvis fluksen halveres, kan kjernetverrsnittet også halveres, om man ønsker å beholde samme flukstetthet. Ved å omforme nettfrekvensen til en høyere verdi, kan man altså overføre samme effekt med en mindre transformator.

Figur 5.36 viser et system hvor en krafttransformator har tilkoblet en frekvensomformer i primærkretsen og en i sekundærkretsen. I det totale regnskapet må en her også ta hensyn til økte kostnader og økte tap på grunn av de to strømrettersystemene. For å oppnå mest mulig sinusformet spenning, vil transformatorfrekvensen begrense seg til noen få kilohertz eller mindre. Det vil likevel redusere byggestørrelsen i stor grad.



Figur 5.36: Høyfrekvenstransformator med strømrettere

Eksempel 15 *En 22000/400 V Dyn11 trefasetransformator tilkoblet et 50 Hz nett har et kjernetverrsnitt A=350 cm*^{2} *og primært vindingstall* $N_1 = 1000$. *Hvilket tverrsnitt gir samme flukstetthet dersom frekvensen økes til 5,0 kHz når spenningsomsetningen er den samme som før?*

Løsning:
Indusert spenning på primærsiden er tilnærmet lik primær fasespenning:

$$E \approx \frac{22000}{\sqrt{3}} = 12700\,\mathrm{V}$$

Maksimal fluks ved $50\,\mathrm{Hz}$ er

$$\phi_{\max} = \frac{E}{4,44 N_1 f} = \frac{12700}{4,44 \cdot 1000 \cdot 50} = 0,0572\,\mathrm{Wb}$$

Maksimal flukstetthet blir

$$B_{\max} = \frac{\phi_{\max}}{A} = \frac{0,0572}{350 \cdot 10^{-4}} = 1,63\,\mathrm{T}$$

Ved en frekvens på $5,0\,\mathrm{kHz}$ blir maksimal fluks

$$\phi_{\max} = \frac{E}{4,44 N_1 f} = \frac{12700}{4,44 \cdot 1000 \cdot 5000} = 572\,\mu\mathrm{Wb}$$

Nødvendig kjernetverrsnitt ved en maksimal flukstetthet $B_{\max} = 1,63\,\mathrm{T}$ reduseres dermed til

$$A = \frac{\phi_{\max}}{B_{\max}} = \frac{572 \cdot 10^{-6}}{1,63} = 3,5 \cdot 10^{-4}\,\mathrm{m}^2 = 3,5\,\mathrm{cm}^2$$

Dette er en teknologi som fortsatt er under utvikling. En annen løsning som det forskes på, er å bygge transformatorstasjoner med kryogen teknologi (superledende viklinger). Da vil viklingsresistansen (og derved strømvarmetapene) elimineres. En må likevel ta med i betraktningen at det medgår en del effekt til å holde anlegget nedkjølt.

5.15 Øvingsoppgaver

1. En enfasetransformator med spenningsomsetning $100/500\,\mathrm{V}$ har 200 tørn på primærsiden. Hvor mange tørn har sekundærviklingen? Regn ut primærstrømmen når sekundærsiden belastes med en resistans på $5,0\,\mathrm{k\Omega}$. Betrakt transformatoren som ideell.

2. En enfasetransformator i tomgang påtrykkes en spenning på $500\,\mathrm{V}$ med en frekvens på $50\,\mathrm{Hz}$. Pirmærspolen har 300 vindinger, og kjerna har et tverrsnitt på $50\,\mathrm{cm}^2$. Hva blir maksimal flukstetthet i kjerna?

3. Tegn ekvivalentskjema og fasordiagram for en belastet transformator.

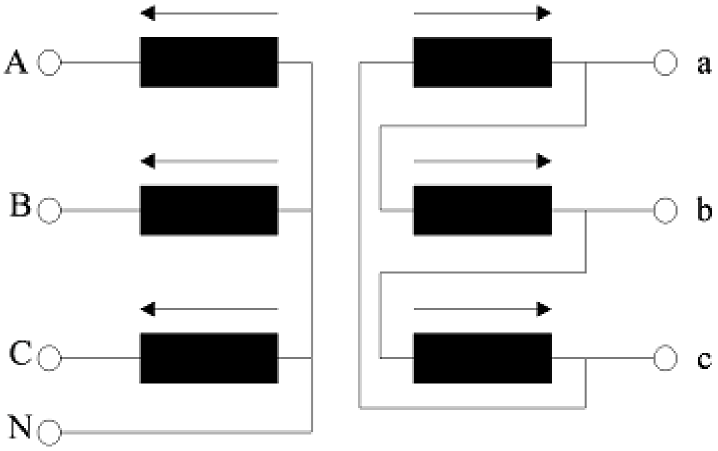
4. En $10\,\mathrm{MVA}$ trefasetransformator med omsetningsforhold $66/22\,\mathrm{kV}$ har viklingsresistanser og lekkreaktanser som angitt i tabell 5.2. Beregn de prosentuelle spenningsfallene sett fra høyspenningssiden. Hva blir lastspenningen ved 75% belastning når effektfaktoren $\cos\varphi = 0,8$ induktiv og primærspenningen ligger på merkeverdi?

Tabell 5.2: Viklingsresistanser og lekkreaktanser ved driftstemperatur

$R_1\,[\Omega]$	$X_1\,[\Omega]$	$R_2\,[\Omega]$	$X_2\,[\Omega]$
$2,2$	10	$0,24$	$1,1$

5. Belastningstapet ved driftstemperatur ($75\,°\mathrm{C}$) for transformatoren i oppgave 4 er $100\,\mathrm{kW}$, og tomgangstapet er $50\,\mathrm{kW}$. Regn ut likestrømstapet og tilleggstapet. Beregn også virkningsgraden ved 70% last og ved 100% last ved $\cos\varphi_2 = 0,8$ induktiv.

6. Bestem koblingsgruppesymbolet for transformatoren på figur 5.37.



Figur 5.37: Trefasetransformator

7. Hvorfor må to parallelle transformatorer ha samme klokketimetall og samme spenningsomsetning i tomgang? Hva hender hvis disse betingelsene ikke er oppfylt?

8. En $5,0\,\mathrm{kVA}$ trefase autotransformator har omsetningsforhold $400/230\,\mathrm{V}$. Beregn merkestrømmene, samt egeneffekten.

9. Hvilke problemer kan oppstå hvis man sikrer målekretsen til en strømtrafo i et høyspent koblingsanlegg? Hvorfor må målekretsen til en spenningstrafo alltid sikres?

10. En elektronisk trafo med omsetningsforhold $22000/400\,\mathrm{V}$ påtrykkes et sinusformet signal med en frekvens på $3,0\,\mathrm{kHz}$. Pirmærspolen har 1000 tørn. Hvilket tverrsnitt må kjerna ha for at flukstettheten ikke skal overskride $1,7\,\mathrm{T}$? Hvilket kjernetverrsnitt kreves ved en frekvens på $50\,\mathrm{Hz}$?

6 Strømrettere

6.1 Ulike typer strømrettere

En elektronisk strømretter er en enhet som ved hjelp av kraftelektronikk knytter sammen to kretser med ulikt spenningsnivå, frekvens eller antall faser. I noen tilfeller er det behov for galvanisk skille. Strømretterne kan deles inn i fire hovedgrupper: Likerettere, vekselrettere, choppere og AC/AC-omformere. Tabell 6.1 viser en oversikt over de ulike omformertypene.

Tabell 6.1: Strømrettere: Hovedtyper og anvendelsesområder

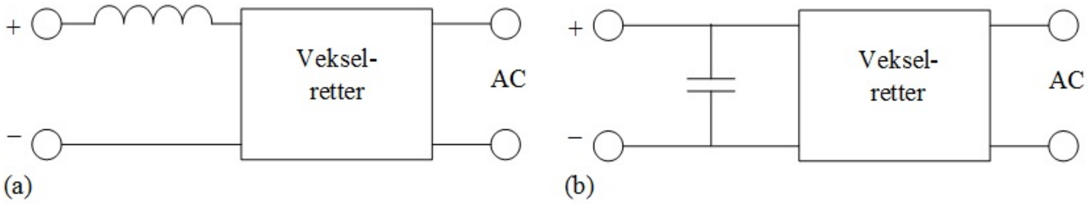
AC/DC-omformere (likerettere)	
Nettført	Selvført
Elektrolyse	Aktive filtre
Høyspent likestrømsoverføring	Styrte likerettere
Magnetisering av synkronmaskiner	
Batteriladere	
Strømforsyninger	
DC/AC-omformere (vekselrettere)	
Nettført	Selvført
Høyspent likestrømsoverføring	Nødstrømforsyninger
DC/DC-omformere (choppere)	
Strømforsyninger	
Spenningstilpassing for solcelleanlegg	
Likestrøms motordrift	
AC/AC-omformere (frekvensomformere)	
Med DC mellomkrets	Direkte omforming
Synkronmotordrift	Cyclokonvertere
Frekvensstyring av asynkronmotorer	Matriseomformere
Vekselretterkaskade for sleperingsmotorer	

Det finnes også en rekke andre omformertyper, men disse er de mest vanlige. Det fins dessuten et vidt spekter av anvendelsesområder som ikke er tatt med i tabellene.

6.2 Strømmating og spenningsmating

Dersom en omformer har en stor induktans på likestrømssiden, vil den forsøke å holde en jevnest mulig likestrøm, selv om likespenningen skulle pulsere. Dette kalles en strømmatet omformer og er vist på figur 6.1a. En likestrømsmotordrift vil være et slikt system, siden motoren vil opptre som en delvis induktiv last.

Dersom likestrømslasten domineres av en kapasitans, slik det er vist på figur 6.1b, vil kretsen forsøke å holde spenningen mest mulig konstant, selv om strømmen skulle pulsere. Vi snakker da om et spenningsmatet system, som for eksempel en likeretter med glattekondensator .



Figur 6.1: Vekselrettere: a) Strømmatet omformer, b) Spenningsmatet omformer

6.3 Diodelikerettere

Som før nevnt er diodelikeretteren nettført og kan derfor i liten grad styres. Den er imidlertid enkelt oppbygd og består av billige komponenter og er derfor mye brukt. En skiller mellom enfase- og trefaseutførelser.

6.3.1 Enveis enpulskobling

Enveis enpulskobling er den enkleste enfaselikeretteren, og den er vist på figur 6.2. Dette er imidlertid en lite brukt kobling, av to grunner: Bare vekselspenningens positive halvperioder slipper gjennom, og derfor blir middelverdien av lastspenning og –strøm ganske lav. Den ideelle tomgangslikespenningen blir

$$U_{di0} = \frac{\sqrt{2}U_v}{2\pi}\int\limits_0^{\pi} \sin(\omega t)\, d\omega t = \frac{\sqrt{2}}{\pi}U_v = 0,45U_v \tag{6.1}$$

hvor U_{di0} er middelverdien av likespenningen i tomgang og U_v er effektivverdien av vekselspenningen.

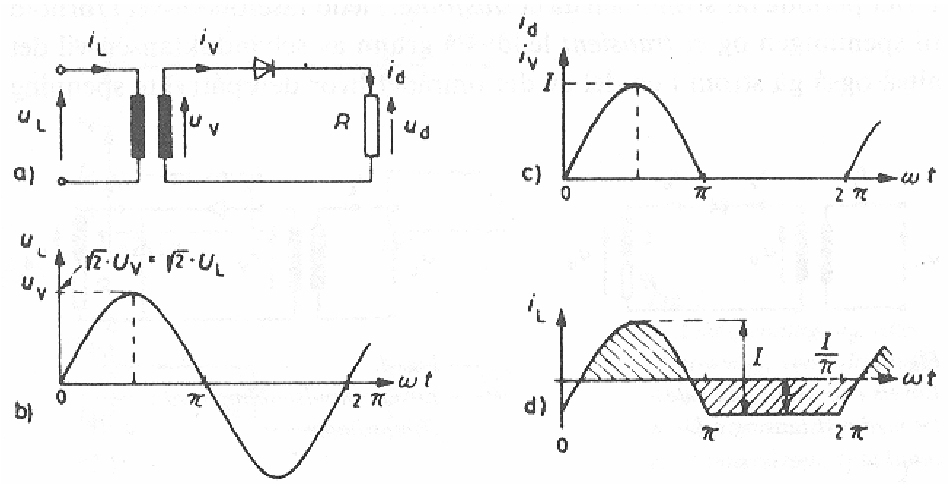
Dessuten vil transformatoren ha en vekselstrømskrets mot nettet og en likestrømskrets mot lasten. Dette gir en magnetisk ubalanse i transformatorkjernen, og primærstrømmen blir forskjøvet i forhold til sekundærstrømmen, som det fremgår av figur 6.2c og 6.2d.

6.3.2 Enveis topulskobling med midtpunktkobling

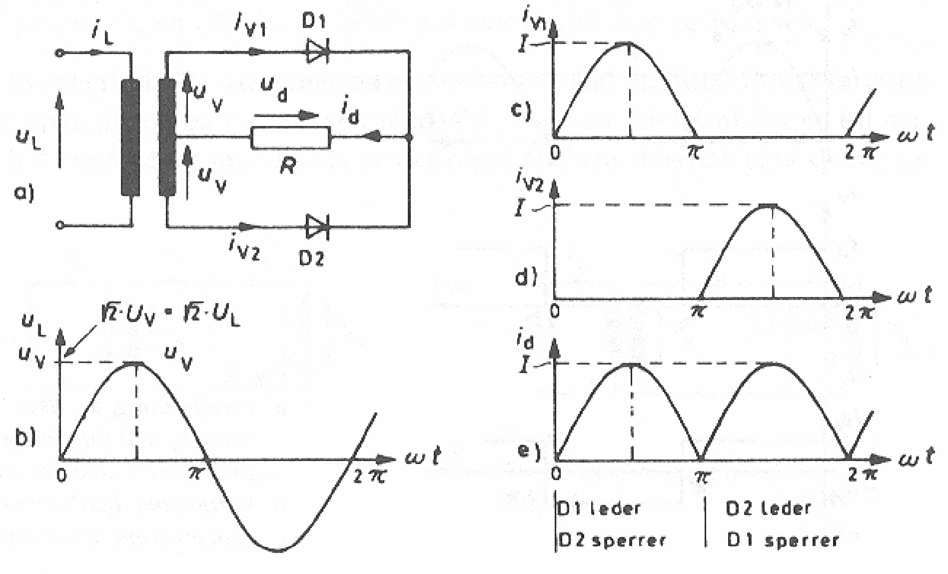
En mye bedre enfaselikeretter er enveis topulskobling med midtpunktkobling. Denne er vist på figur 6.3. Sekundærspolen er delt i to halvdeler, koblet til hver sin diode D1 og D2. D1 vil slippe gjennom strømmens positive halvperiode, og D2 slipper gjennom den negative. Dermed vil to pulser slippe gjennom per periode, og middelverdien av strøm og spenning på DC-siden blir høyere.

Middelverdien av likespenningen ved tomgang er gitt ved formel (6.2):

$$U_{di0} = \frac{\sqrt{2}U_v}{\pi}\int\limits_0^{\pi} \sin(\omega t)\, d\omega t = \frac{2\sqrt{2}}{\pi}U_v = 0,9U_v \tag{6.2}$$



Figur 6.2: Koblingsskjema og kurveformer for enveis enpulskobling



Figur 6.3: Koblingsskjema og kurveformer for enveis topulskobling med midtpunktkobling

altså dobbelt så høy som ved enpulskoblingen.
Likestrømmens middelverdi blir

$$I_d = \frac{2}{\pi} I_m = 0,638 \cdot I_m \tag{6.3}$$

hvor I_m er likestrømmens toppverdi.
Noe som også er viktig, er hvilken maksimal sperrespenning diodene blir påkjent med når de ikke leder. Denne er gitt ved formel (6.4):

$$U_{s\,\max} = 2\sqrt{2} U_v \tag{6.4}$$

Dersom en glattespole settes i serie med resistansen på figur 6.3, blir sekundærstrømmens effektivverdi

$$I_v = \frac{1}{\sqrt{2}} I_d \tag{6.5}$$

Eksempel 1 *En likestrømslast på* $10\,\Omega$ *er tilkoblet en transformator med midtpunktuttak og omsetningsforhold 230/2x20 V. Kretsen er koblet opp som vist på figur 6.3. Beregn likespenningen* U_d *og linjestrømmen* I_L *når vi betrakter diodene som ideelle. Hvor stor spenning utsettes diodene for i sperreretning?*

Løsning:
Likespenningen blir

$$U_d \approx U_{di0} = 0,9 \cdot U_v = 0,9 \cdot 20 = 18\,\mathrm{V}$$

Likestrømmen blir:

$$I_d = \frac{U_d}{R} = \frac{18}{10} = 1,8\,\mathrm{A}$$

Vekselstrømmens effektivverdi på sekundærsiden:

$$I_v = \frac{I_d}{\sqrt{2}} = \frac{1,8}{\sqrt{2}} = 1,27\,\mathrm{A}$$

I utregningen av primær linjestrøm I_L, benytter en det omvendte omsetningsforholdet. Linjestrømmen blir da

$$I_L = \sqrt{2} I_v \frac{U_{2N}}{U_{1N}} = 1,8 \cdot \frac{20}{230} = 156\,\mathrm{mA}$$

Maksimal sperrespenning blir

$$U_{s\ \max} = 2\sqrt{2} U_v = 2\sqrt{2} \cdot 20 = 57\,\mathrm{V}$$

6.3.3 Toveis topulskobling, enfase brokobling

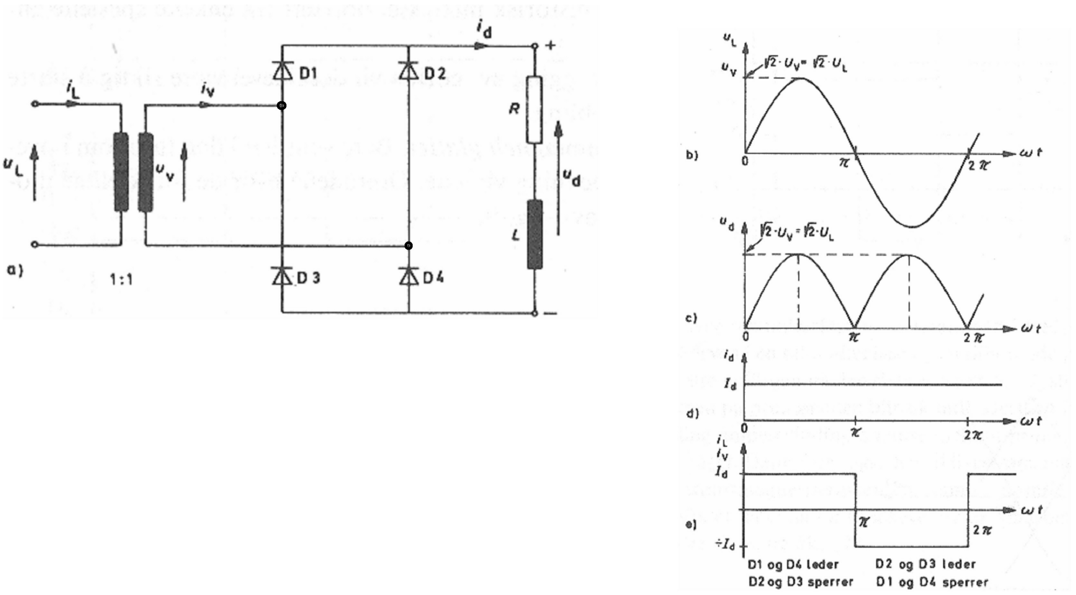
Et annet alternativ for topulskobling av enfaselikerettere, er enfase brokobling som er vist på figur 6.4. Dette er en svært vanlig likeretterkobling. Den krever fire dioder, men sekundærspolen kan kobles direkte uten midtuttak. Ved positiv halvperiode leder diodene D1 og D4, og ved negativ halvperiode leder diodene D2 og D3. Siden likespenningen passerer over to dioder i serie, vil det totale diodespenningsfallet bli dobbelt så stort som for midtpunktkoblingen. For øvrig vil likespenningen ha samme kurveform som for foregående krets, og også i dette tilfelle er tomgangslikespenningen gitt ved formel (6.2). Maksimal relativ sperrespenning blir imidlertid mindre, siden diodene ikke blir belastet av to spolehalvdeler i serie:

$$U_{s\max} = \sqrt{2} U_v \tag{6.6}$$

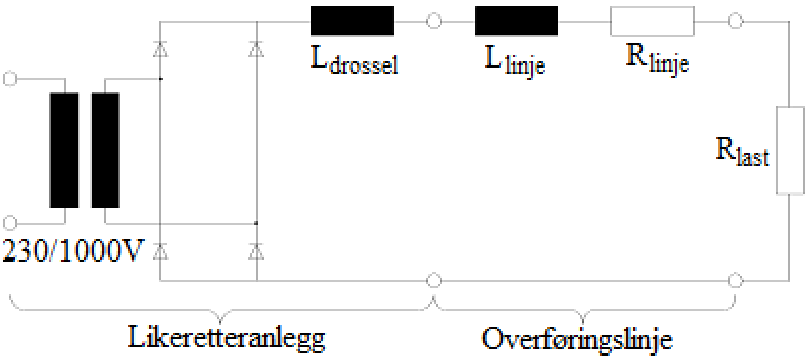
Det er verdt å merke seg at kretsen på figur 6.4 har en delvis induktiv last med høy induktans. Derfor er likestrømmen i_d glatt, og vekselstrømmen i_v får en firkantpulsfasong. Sekundærstrømmens effektivverdi er lik likestrømmens middelverdi:

$$I_v = I_d \tag{6.7}$$

Dersom lasten var rent resistiv, ville i_d hatt samme form som u_d, og vekselstrømmen i_v ville vært sinusformet.



Figur 6.4: Koblingsskjema og kurveformer for toveis topulskobling



Figur 6.5: Likeretter med likestrømslinje og resistiv last

Eksempel 2 *En lang høyspent overføringslinje til en resistiv last benytter likestrøm for å redusere de reaktive tapene. Spenningen inn på likeretteren er 1000 V. Oppkoblingen er vist på figur 6.5. Drosselen benyttes for å glatte likestrømmen og er så stor at likestrømmen blir helt glatt. Regn ut likestrømmen når summen av resistansene i likestrømskretsen* $R_{total} = 500\,\Omega$*.*

Løsning:
Likespenningens middelverdi er

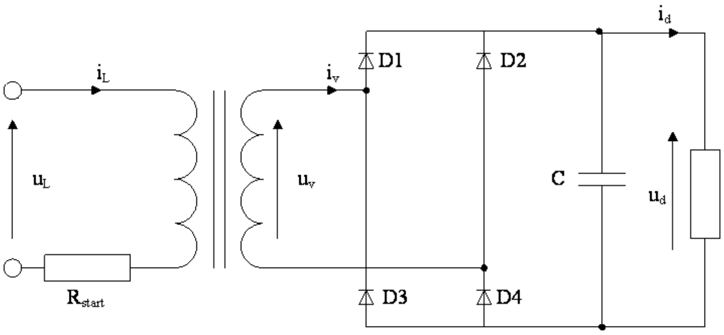
$$U_{di0} = 0,9 \cdot U_v = 0,9 \cdot 1000 = 900\,\mathrm{V}$$

Likestrømmen er

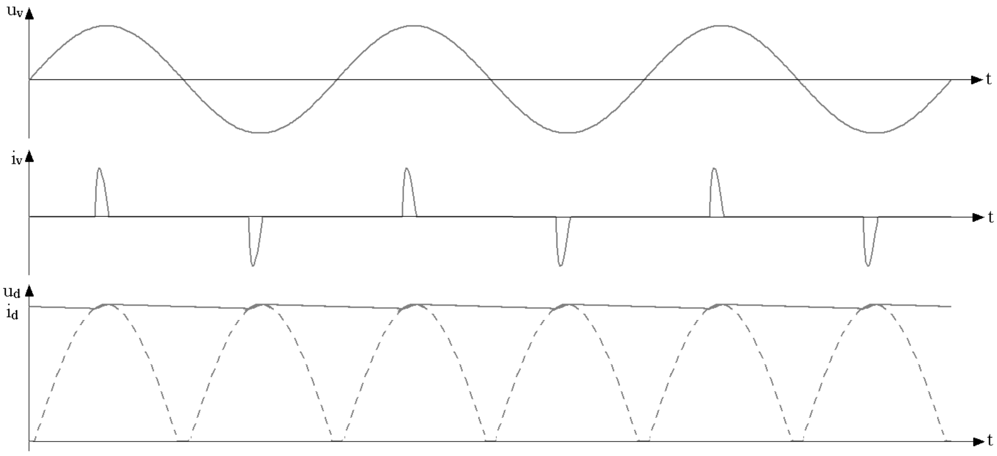
$$I_d = \frac{U_{di0}}{R_{total}} = \frac{900}{500} = 1,8\,\mathrm{A}$$

For en primitiv batterilader eller en likestrøms motordrift kan kretsen på figur 6.4 være tilstrekkelig, men for en strømforsyning til en elektronikkrets vil det være uforholdsmessig mye rippel.

Ved å tilføre en glattekondensator som vist på figur 6.6, vil likespenningen inneholde mye mindre rippel, som det fremgår av figur 6.7. Ved oppstart vil en utladet kondensator opptre som en kortslutning, og derfor er en lavohmig motstand koblet i serie med primærspolen for å begrense startstrømmen. Det er også verdt å merke seg vekselstrømmen i_v utelukkende består av korte pulser.



Figur 6.6: Toveis topulskobling med glattekondensator (C-filter)



Figur 6.7: Strømmer og spenninger for diodelikeretter med C-filter

Størrelsen på spenningsrippelet er bestemt av rippelfrekvensen (2 ganger nettfrekvensen for en topulskrets), størrelsen på glattekondensatoren og laststrømmen og er gitt ved formel (6.8):

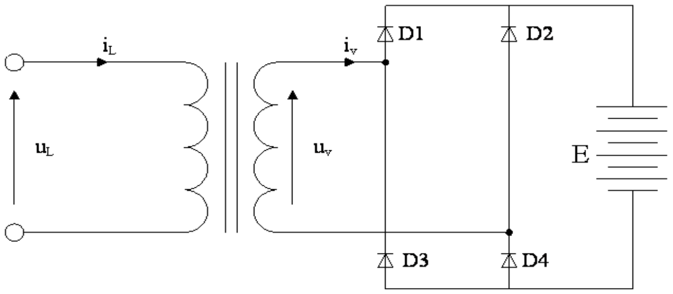
$$U_{rippel} = \frac{I_d}{C \cdot f_{rippel}} \tag{6.8}$$

Tomgangslikespenningen vil være lik vekselspenningens amplitude:

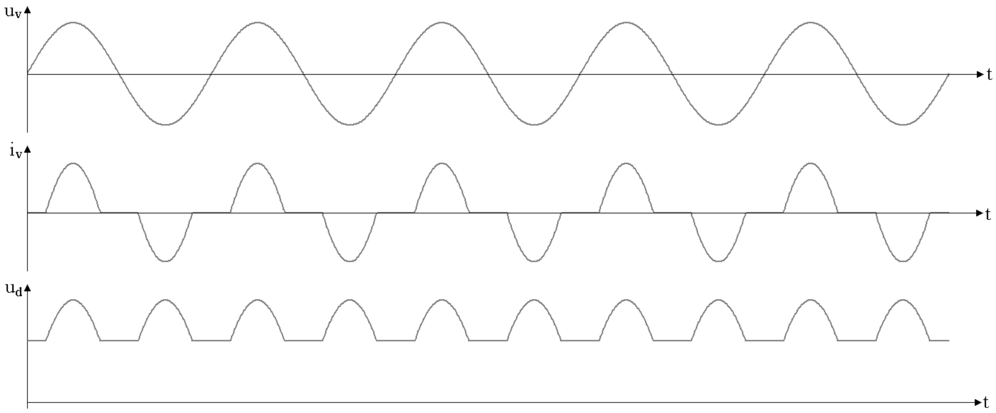
$$U_{di0} = \sqrt{2} \cdot U_v \tag{6.9}$$

En lignende situasjon får man når diodelikeretteren anvendes som batterilader, som vist på figur 6.8. Vekselstrømmen blir også her diskontinuerlig, om enn ikke i samme grad som for ovenstående kobling. Likespenningen vil bestå av to ladepulser per periode, og mellom ladepulsene er utgangsspenningen lik batterispenningen. Dette fregår av figur 6.9.

Eksempel 3 *Vi skal lage en strømforsyning som avgir* $10,5$ *V og* $1,0$ *A DC. Rippelet skal ikke være mer enn* $2,0$ *% av merkespenning ved merkedrift. Hver av diodene har et spenningsfall på* $0,7$ *V. Transformatoren har en merkeeffekt på* 20 *VA og tilkobles* 230 *V nettspenning med en frekvens på* 50 *Hz. Beregn omsetningsforholdet til transformatoren. Beregn også størrelsen på strømbegrensningsmotstanden* R_{start} *og glattekondensatoren* C *når transformatoren er ventet å klare tjue ganger merkestrøm ved oppstart. Hvor stor sperrespenning må diodene tåle?*



Figur 6.8: Diodelikeretter som batterilader



Figur 6.9: Strømmer og spenninger for batterilader

Løsning:
Rippelspenningen er

$$10,5 \cdot 0,02 = 210\,\mathrm{mV}$$

Høyeste utgangsspenning blir da 10,6V, siden rippelet både vil ligge litt over og litt under utgangsspenningens middelverdi.
Sekundærspenningens toppverdi må da være

$$10,6 + 2 \cdot 0,7 = 12,0\,\mathrm{V}$$

Effektivverdien blir da

$$U_v = \frac{12,0}{\sqrt{2}} = 8,5\,\mathrm{V}$$

Transformatoren må da ha et omsetningsforhold på $230/8,5\,\mathrm{V}$.
Største tillatte primærstrøm er

$$\frac{20\,\mathrm{V\,A}}{230\,\mathrm{V}} \cdot 20 = 1,74\,\mathrm{A}$$

Det krever en strømbegrensningsmotstand

$$R_{start} = \frac{230\,\mathrm{V}}{1,74\,\mathrm{A}} = 132\,\Omega$$

Kondensatoren må ha en størrelse

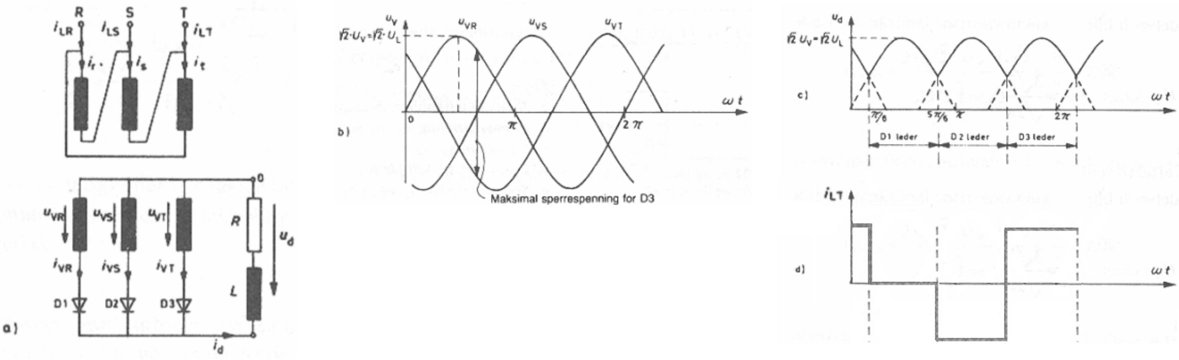
$$C = \frac{I_d}{U_{rippel} \cdot f_{rippel}} = \frac{1}{0,21 \cdot 100} = 47600\,\mu\mathrm{F}$$

Diodenes høyeste sperrespenning vil være

$$\sqrt{2} \cdot 8,5 = 12\,\mathrm{V}$$

6.3.4 Enveis trepulskobling

I store anlegg vil det være naturlig å bruke trefaselikerettere. Den enkleste av disse er enveis trepulskobling som er vist på figur 6.10. Koblingen er lite brukt og kan, i likhet med enveis enpulskobling, skape magnetisk ubalanse i transformatoren ved enkelte transformatorkoblinger. Dy-koblingen på figur 6.10 skaper imidlertid ingen problemer. Den av diodene D1 til D3 som til enhver tid har høyest spenning, vil lede. Derfor vil likespenningen se ut som på figur 6.10c. Det er åpenbart at trefaselikeretteren gir lavere spenningsrippel enn enfaselikeretteren.



Figur 6.10: Koblingsskjema og kurveformer for enveis trepulskobling

Likespenningens middelverdi ved tomgang er

$$U_{di0} = \frac{1}{\frac{2\pi}{3}} \int_{\frac{\pi}{6}}^{\frac{5\pi}{6}} \sqrt{2} U_v \sin{(\omega t)}\, d\omega t = \frac{3\sqrt{3}}{\sqrt{2}\pi} U_v = 1,17 U_v \tag{6.10}$$

hvor U_v er definert som sekundær fasespenning.
Maksimal sperrespenning for diodene er

$$U_{s\,\max} = \sqrt{3} \cdot \sqrt{2} U_v = 2,45 U_v \tag{6.11}$$

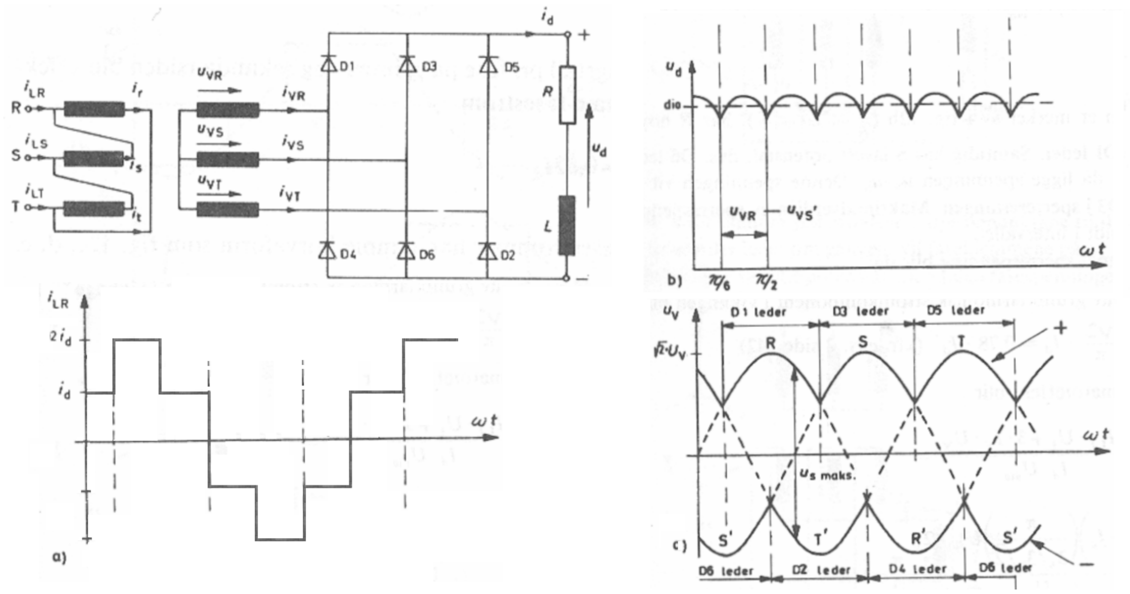
Sekundær fasestrøm med glattespole:

$$I_v = \frac{1}{\sqrt{3}} I_d = 0,58 I_d \tag{6.12}$$

6.3.5 Toveis sekspulskobling, trefase brokobling

Figur 6.11 viser toveis sekspulskobling, som er den mest vanlige trefasekoblingen.
En ser av figuren at rippelet blir enda mindre enn for trepulskoblingen. Sammenligner en figur 6.10 og figur 6.11, kan en forestille seg brokoblingen som to trepulskoblinger som er 60 grader faseforskjøvet og hvor en er koblet til plusspolen og en til minuspolen på likestrømssiden. Likespenningens verdi vil hele tiden være den loddrette avstanden mellom de to heltrukne linjene på figur 6.11a, og den vil ha en kurveform som vist på figur 6.11b, med seks pulser per nettperiode. Siden sekundærkretsen vil føre en vekselstrøm, unngår en magnetisk ubalanse i transformatorkjernen.
Dette er en relativt enkel krets, og en kan benytte en vanlig trefasetransformator uten delte viklinger og andre tilleggskomponenter.
Likespenningens middelverdi er

$$U_{di0} = \frac{3\sqrt{3}}{\pi} \sqrt{2} U_v = 2,34 U_v \tag{6.13}$$



Figur 6.11: Koblingsskjema og kurveformer for toveis sekspulskobling med strømmatet DC-krets

Maksimal sperrespenning blir

$$U_{s\max} = \sqrt{3} \cdot \sqrt{2} U_v = 2,45 U_v \tag{6.14}$$

som er det samme som for enveis trepulskobling.
Ved bruk av glattespole blir effektivverdien av sekundær fasestrøm

$$I_v = \sqrt{\frac{2}{3}} I_d = 0,82 I_d \tag{6.15}$$

Eksempel 4 *En stor 220 V likestrømsmotor forsynes av en trefase likeretterkobling som vist på figur 6.11. Kretsen er forsynt fra et 230 V nett. Hvilket omsetningsforhold må transformatoren ha for at motoren skal forsynes med merkespenning? Hvor høy sperrespenning blir diodene utsatt for?*

Løsning:
Middelverdien av likespenningen må være $220\,\mathrm{V}$. Sekundær fasespenning blir da

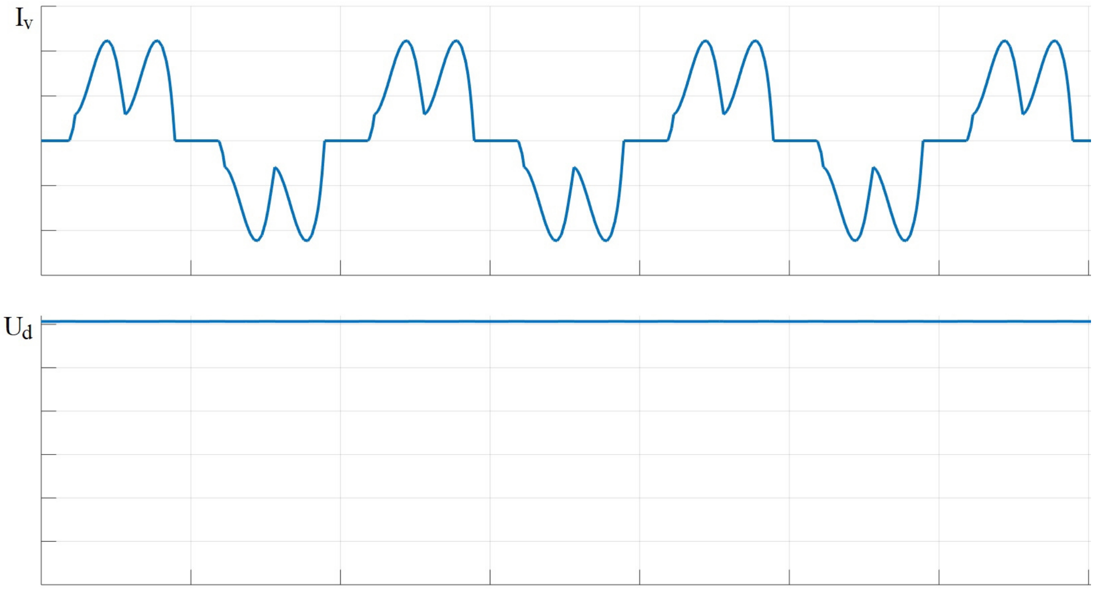
$$U_v = \frac{U_{di0}}{2,34} = \frac{220}{2,34} = 94\,\mathrm{V}$$

Sekundær linjespenning blir

$$\sqrt{3} U_v = \sqrt{3} \cdot 94 = 163\,\mathrm{V}$$

Omsetningsforholdet blir dermed $230/163\,\mathrm{V}$.
Maksimal sperrespenning er

$$U_{s\ \max} = \sqrt{6} U_v = \sqrt{6} \cdot 94 = 230\,\mathrm{V}$$

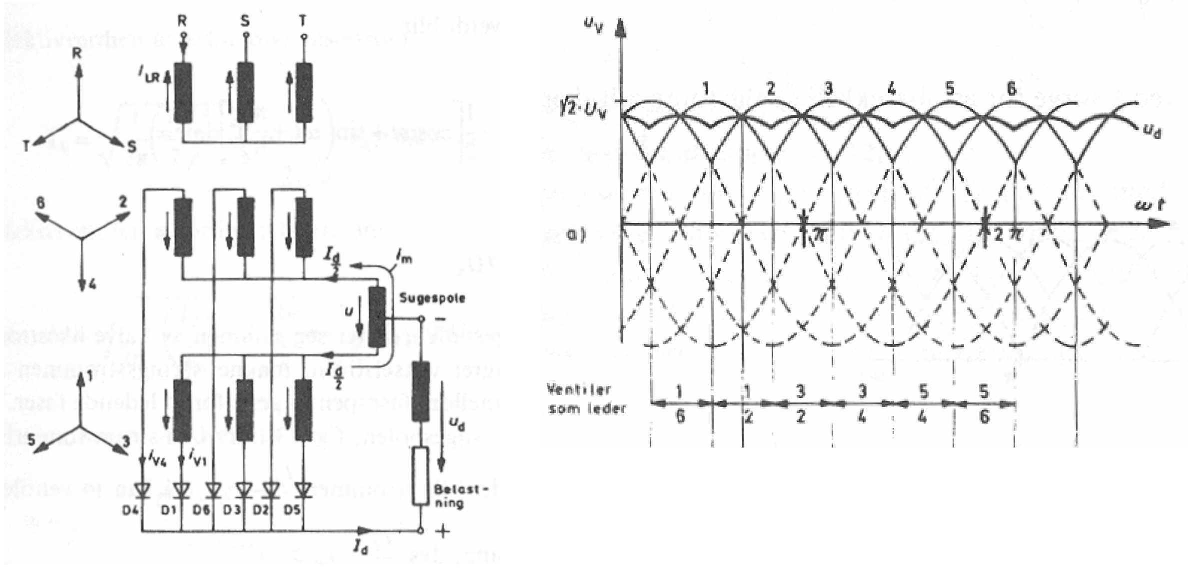


Figur 6.12: Koblingsskjema og kurveformer for toveis sekspulskobling med spenningsmatet DC-krets

Figur 6.11 viser strømmer og spenninger for en strømmatet omformer. Dersom omformeren er spenningsmatet, blir kurveformer for vekselstrøm og likespenning som på figur 6.12. Vekselstrømmen inneholder ladepulser, og likespenningen er glatt.

6.3.6 Enveis sekspulskobling med sugespole

En annen måte å generere sekspulskobling, er å benytte en transformator med delte sekundærviklinger som er stjernekoblet, hvor det ene settet er koblet med omvendt polaritet. I realiteten har en da et seksfasesystem som vil gi seks pulser per periode. Ved å koble viklingssettene sammen over en sugespole i stedet for å koble nullpunktene direkte sammen, får en ut en glattere likespenning og oppnår en bedre utnyttelse av transformatoren. Koblingen er vist på figur 6.13.



Figur 6.13: Koblingsskjema og kurveformer for enveis sekspulskobling med sugespole

Likespenningens middelverdi blir som ved enveis trepulskobling:

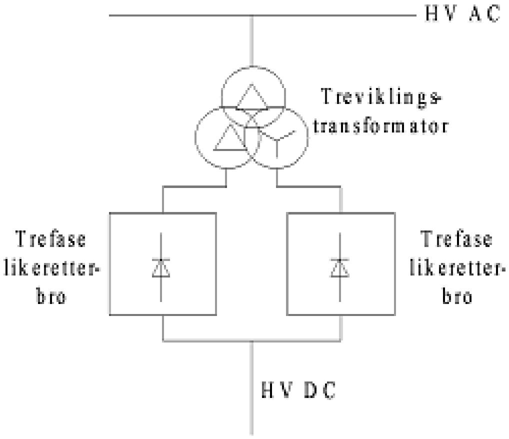
$$U_{di0} = \frac{3\sqrt{3}}{\sqrt{2}\pi} U_v = 1,17 U_v \tag{6.16}$$

Maksimal sperrespenning vil også være den samme som for de to foregående trefasekoblingene, gitt ved formel (6.11) og (6.14).
Ved bruk av glattespole blir effektivverdien av sekundær fasestrøm

$$I_v = \frac{1}{2\sqrt{3}} I_d = 0,29 I_d \tag{6.17}$$

6.3.7 Toveis tolvpulskobling

Hvis man serie- eller parallellkobler to trefase brokoblinger, hvor den ene er koblet til en deltakoblet sekundærvikling og den andre til en y-koblet sekundærvikling på en treviklingstransformator, oppnår man en toveis tolvpulskobling. Dette skyldes at de to sekundærkretsene er 30 grader faseforskjøvet. Koblingen er vist på figur 6.14 og brukes mye ved høyspent likestrømsoverføring (HVDC) for å oppnå en glattest mulig likespenning.



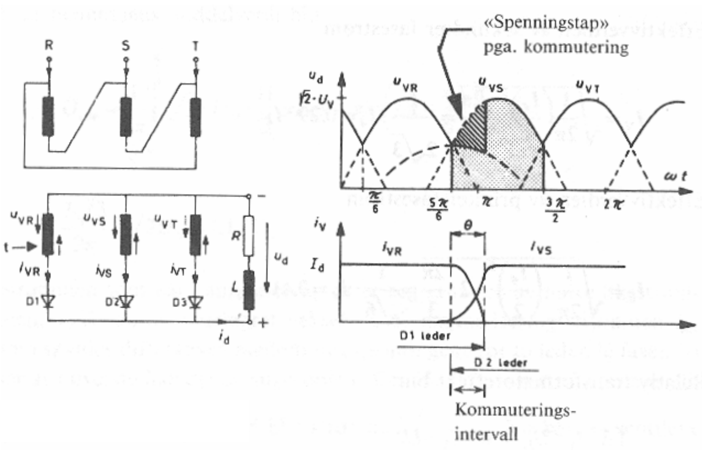
Figur 6.14: Blokkskjema for høyspent toveis tolvpulskobling

6.3.8 Kommuteringsintervall

I en ideell likeretter vil strømmen momentant skifte fra en diode til en annen. På grunn av reaktans i transformatoren, vil strømmen i virkeligheten bygge seg gradvis opp i en fase mens den gradvis avtar i en annen. I denne fasen vil begge greinene være ledende og dermed ligge på samme spenningsnivå. Dette er vist på figur 6.15 for en enveis trepulskobling. En ser at kommuteringen lager et slags innsnitt i likespenningskurven, og jo større likestrøm kretsen fører, jo lenger tid vil kommuteringen ta. Spenningsfallet U_{dx} som skyldes kommuteringen er altså proporsjonalt med likestrømmen I_d. Det vil også være proporsjonalt med transformatorens lekkreaktans X_t som tilsvarer lekkreaktansen sett fra sekundærsiden.
Dette spenningsfallet kan skrives på flere måter:

$$U_{dx} = U_{di0} \cdot \frac{1 - \cos\theta}{2} = \frac{q}{2\pi r} X_t I_d \tag{6.18}$$

hvor θ er kommuteringsintervallets vinkelmessige utstrekning, q er antall pulser per periode og r er antall likerettergrupper.



Figur 6.15: Kommuteringsintervall for enveis trepulskobling

Den resulterende likespenningen når kommuteringsspenningsfallet er trukket fra, gis da ved

$$U_d = U_{di0} - U_{dx} \tag{6.19}$$

Dersom likeretteren er utstyrt med glattekondensator, vil det ikke oppstå kommutering, fordi den ene fasen er blitt strømløs før den neste begynner å lede. En ser av figur 6.7 at likespenningen er tilnærmet lik toppverdien av vekselspenningen, men med et visst spenningsrippel på toppen. Likespenningen blir følgelig:

$$U_d = \sqrt{2}U_v - 0,5U_{rippel} = \sqrt{2}U_v - \frac{I_d}{2Cf_{rippel}} \tag{6.20}$$

Dersom likespenningen er lav, må en også ta spenningsfallet over diodene med i beregningen. Ved høye likespenninger blir dette spenningsfallet ubetydelig.

Spenninger og spenningsfall de ulike likerettertypene kan sammenfattes i det følgende::
Enveis topulskobling med midtpunktkobling:

$$\begin{gathered} U_{di0} = \frac{2\sqrt{2}}{\pi} U_v \\ U_{dx} = \frac{X_t I_d}{\pi} \\ U_d = \frac{2\sqrt{2}}{\pi} U_v - \frac{X_t I_d}{\pi} \end{gathered} \tag{6.21}$$

Toveis topulskobling, enfase brokobling:

$$\begin{gathered} U_{di0} = \frac{2\sqrt{2}}{\pi} U_v \\ U_{dx} = \frac{2X_t I_d}{\pi} \\ U_d = \frac{2\sqrt{2}}{\pi} U_v - \frac{2X_t I_d}{\pi} \end{gathered} \tag{6.22}$$

Enveis trepulskobling:

$$\begin{gathered} U_{di0} = \frac{3\sqrt{3}}{\sqrt{2}\pi} U_v \\ U_{dx} = \frac{3X_t I_d}{2\pi} \\ U_d = \frac{3\sqrt{3}}{\sqrt{2}\pi} U_v - \frac{3X_t I_d}{2\pi} \end{gathered} \tag{6.23}$$

Toveis sekspulskobling, trefase brokobling:

$$\begin{gathered} U_{di0} = \frac{3\sqrt{3}\sqrt{2}}{\pi} U_v \\ U_{dx} = \frac{3X_t I_d}{\pi} \\ U_d = \frac{3\sqrt{3}\sqrt{2}}{\pi} U_v - \frac{3X_t I_d}{\pi} \end{gathered} \tag{6.24}$$

Enveis sekspulskobling med sugespole:

$$\begin{gathered} U_{di0} = \frac{3\sqrt{3}}{\sqrt{2}\pi} U_v \\ U_{dx} = \frac{3X_t I_d}{4\pi} \\ U_d = \frac{3\sqrt{3}}{\sqrt{2}\pi} U_v - \frac{3X_t I_d}{4\pi} \end{gathered} \tag{6.25}$$

Eksempel 5 *Kretsen på figur 6.11 har en sekundær fasespenning* $U_v = 400\,\mathrm{V}$. *Likestrømmen* $I_d = 50\,\mathrm{A}$ *ved merkelast, og transformatorens lekkreaktans sett fra lastsiden er* $X_t = 2{,}0\,\Omega$. *Beregn likespenningen ved tomgang og ved merkelast.*

Løsning:
Likspenningen ved tomgang er

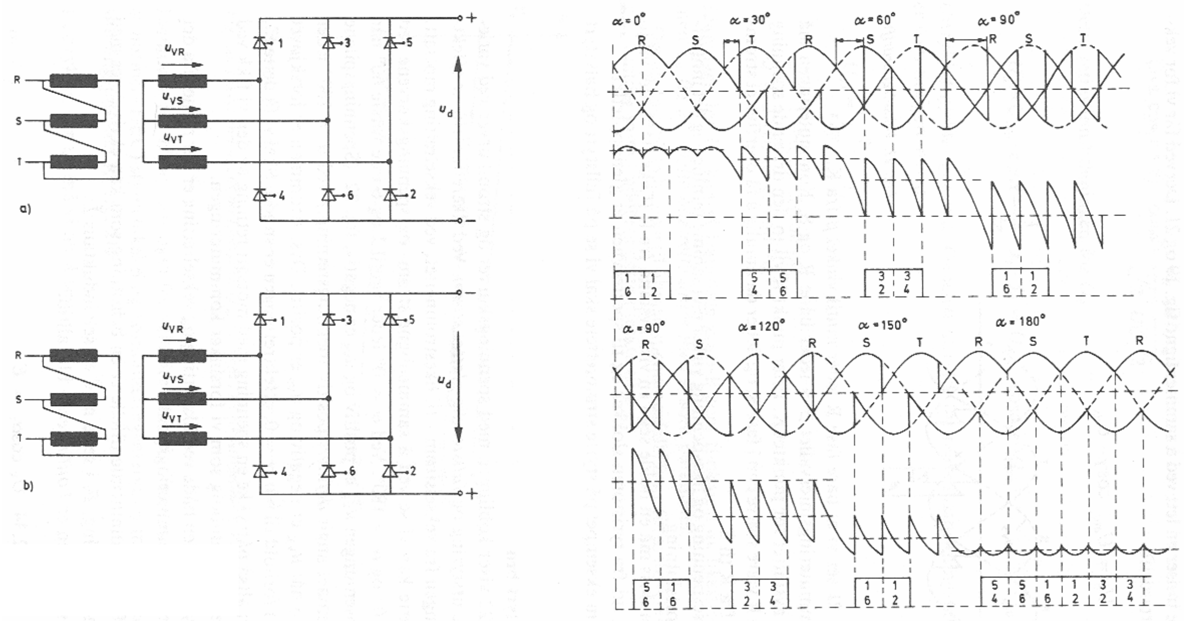
$$U_{dio} = \frac{3\sqrt{6}}{\pi} U_v = \frac{3\sqrt{6}}{\pi} \cdot 400 = 937\,\mathrm{V}$$

Likespenningen ved merkelast er

$$U_d = \frac{3\sqrt{6}}{\pi} U_v - \frac{3X_t I_d}{\pi} = \frac{3\sqrt{6}}{\pi} \cdot 400 - \frac{3 \cdot 2{,}0 \cdot 50}{\pi} = 840\,\mathrm{V}$$

6.4 Fullstyrt bro

Dersom man erstatter diodene i likeretterbroene på figur 6.4 eller 6.11 med tyristorer, kan man styre utgangsspenningen på likeretteren og sågar drive den som vekselretter. Forutsetningen er at likestrømskretsen har en høy induktans som gir en glatt likestrøm, altså et strømmatet system. En slik fullstyrt bro er vist på figur 6.16.



Figur 6.16: Fullstyrt bro. Øverst: likeretterdrift, nederst: vekselretterdrift

På figuren tenner tyristorene til å begynne med så snart spenningen i respektive fase er høyest (plusspol) eller lavest (minuspol). Deretter forsinkes tenningen med 30 grader, så med seksti grader, og etter hvert med nitti grader. En legger merke til at middelverdien av likespenningen avtar når tyristorene forsinkes, og ved nitti grader forsinkelse er middelspenningen null volt. Hvis en fortsetter å øke forsinkelsen, som vist på nedre del av figuren, vil middelspenningen begynne å øke igjen, men med motsatt polaritet, og spenningen når et maksimum ved en tennvinkel $\alpha = 180$ grader. Ved $\alpha = 0$ grader er strøm og spenning motsatt rettet, noe som kjennetegner en last, mens de går i samme retning ved $\alpha = 180$ grader, noe som kjennetegner en kilde. Omformeren har dermed gått over fra å være likeretter til å være vekselretter.
En fullstyrt bro kan med andre ord både regulere likespenningen og retningen på lastflyten gjennom å endre polariteten på likespenningen.

Ser vi bort fra kommuteringsintervallet, er likespenningens middelverdi gitt ved

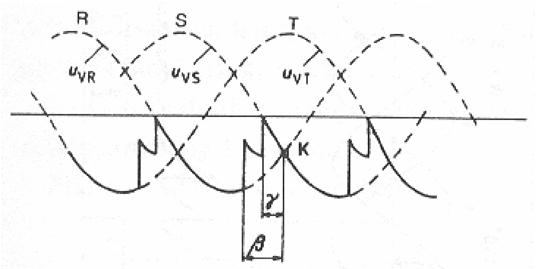
$$U_{di} = U_{di0} \cdot \cos\alpha \tag{6.26}$$

Tar en dessuten med kommuteringsspenningsfallet, vil likespenningens middelverdi være

$$U_d = U_{di0} \cdot \cos\alpha - U_{dx} \tag{6.27}$$

hvor U_{dx} er definert i formel (6.18) og (6.21) – (6.25).

I noen tilfeller velger en å definere styrevinkelen β og kommuteringsmargin γ målt fra kortslutningspunktet K ved vekselretterdrift. Disse vinklene er vist på figur 6.17.



Figur 6.17: Styrevinkel og kommuteringsmargin ved vekselretterdrift

Da vil vekselretterens midlere likespenning være definert ved

$$U_d = U_{di0} \cos\gamma - U_{dx} \tag{6.28}$$

Disse formlene gjelder så lenge likestrømmen er kontinuerlig. Dersom induktansen ikke er i stand til å opprettholde strømmen hele tiden, får vi såkalt luket strøm, og beregningen av likespenningen blir mer komplisert. Spenningsreguleringen blir mye mer ulineær ved luket strøm, så det er en tilstand vi forsøker å unngå.

Eksempel 6 *En stor likestrømsmotor forsynes fra en 50kVA Dyn5-koblet trefasetransformator med omsetningsforhold 22000/400 V. Transformatoren er merket med følgende prosentuelle spenningsfall:* $e_r = 2,5\%$, $e_z = 6,0\%$. *Motoren er merket med* $U_N = 400\,\mathrm{V}$ *og* $I_N = 100\,\mathrm{A}$. *Det benyttes en toveis sekspuls fullstyrt brolikeretter. Hvilken styrevinkel må benyttes for at motoren skal gå med merkelast? Hvilken styrevinkel må benyttes hvis motoren går med halv spenning og med merkestrøm?*

Løsning:
Vi vet fra kapittel 5 at kortslutningsreaktansen er gitt ved

$$X_k{}'' = e_x \frac{U_{2N}}{\sqrt{3} I_{2N}}$$

Sekundær merkestrøm er

$$I_{2N} = \frac{S_N}{\sqrt{3} U_{2N}} = \frac{50000}{\sqrt{3} \cdot 400} = 72,2\,\mathrm{A}$$

Relativ reaktansspenning er

$$e_x = \sqrt{e_z{}^2 - e_r{}^2} = \sqrt{6,0^2 - 2,5^2} = 5,45\%$$

Kortslutningsreaktansen sett fra sekundærsiden er da

$$X_t = X_k{}'' = 0,0545 \cdot \frac{400}{\sqrt{3} \cdot 72,2} = 0.174\,\Omega$$

Kommuteringsspenningfallet ved merkestrøm blir da

$$U_{dx} = \frac{3X_t I_d}{\pi} = \frac{3 \cdot 0,174 \cdot 100}{\pi} = 16,6\,\mathrm{V}$$

Tomgangsspenningen må da være

$$U_{di0} = 2,34 \cdot 230 = 538\,\mathrm{V}$$

Spenningene i kretsen fordeler seg slik:

$$U_{di0} \cos\alpha - U_{dx} = U_N$$

Det skulle gi følgende styrevinkel:

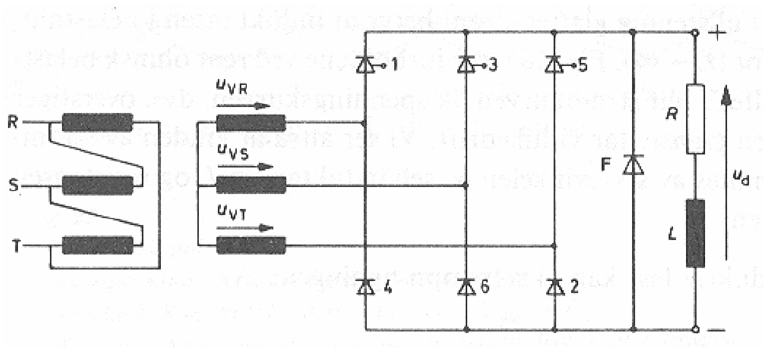
$$\begin{aligned} \cos\alpha &= \frac{U_N + U_{dx}}{U_{di0}} \\ \alpha &= \arccos\left(\frac{U_N + U_{dx}}{U_{di0}}\right) = \arccos\left(\frac{400 + 16,6}{538}\right) = 39,2\,^\circ \end{aligned}$$

Hvis motoren går med halv spenning og med merkestrøm, vil kommuteringspenningsfallet være uendret, mens klemmespenningen reduseres til $U = 200\,\mathrm{V}$. Styrevinkelen blir da

$$\alpha = \arccos\left(\frac{U + U_{dx}}{U_{di0}}\right) = \arccos\left(\frac{200 + 16,6}{538}\right) = 66,3\,^\circ$$

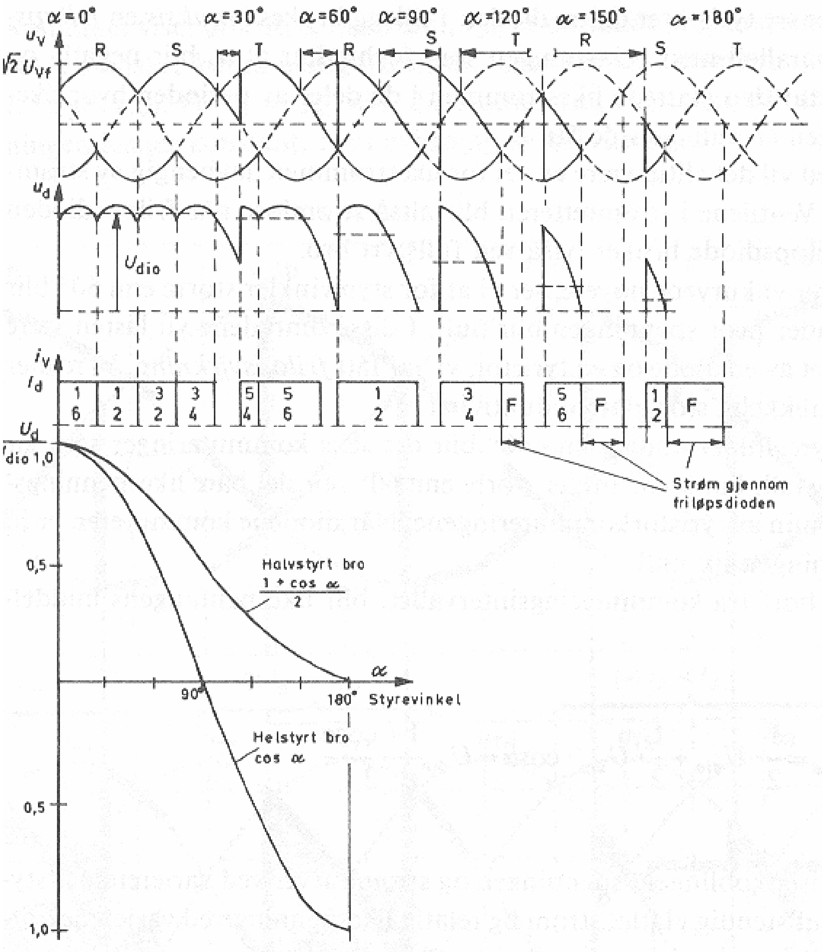
6.5 Halvstyrt bro

Kretsen på figur 6.18 har mye til felles med den foregående, men i nedre del av figuren er tyristorene erstattet med dioder. I tillegg er det satt en friløpsdiode F parallelt med lasten. Denne sørger for at likespenningen u_d ikke blir negativ, og den sørger også for at likestrømmen har en vei å gå hvis alle tyristorene skulle sperre samtidig.



Figur 6.18: Halvstyrt bro

Som det fremgår av figur 6.19, kan ikke en halvstyrt bro brukes som vekselretter. Den egner seg derimot godt som en styrt likeretter, hvor en ønsker å kontrollere den midlere likespenningen.



Figur 6.19: Spenningsforhold for halvstyrt bro

Ser man bort fra kommuteringsspenningsfallet, blir likespenningens middelverdi

$$U_{di} = U_{di0}\frac{1 + \cos\alpha}{2} \tag{6.29}$$

Eksempel 7 *En halvstyrt trefasebro skal forsyne en likestrøms samleskinne med en likespenning som skal ha en konstant middelverdi på* 1500 *V og en likestrøm som skal ligge konstant på* 100 *A. Omformeren er forsynt fra nettet gjennom en trefasetransformator som har et omsetningsforhold på* $22000/1500$ *V og en kortslutningsreaktans på* $1,5\ \Omega$*. Nettspenningen varierer mellom* $23,5$ *kV og* 21 *kV. Beregn midlere tomgangslikespenning, kommuteringsspenningsfall, samt største og minste styrevinkel. Hvor høy sperrespenning må tyristorene tåle?*

Løsning:
Forholdet mellom midlere tomgangslikespenning og sekundær fasespennning er lik

$$U_{di0} = \frac{3\sqrt{3}}{\pi}\sqrt{2}U_v$$

Forholdet mellom likespenningen og sekundær linjespenning må derfor være

$$U_{di0} = \frac{3\sqrt{2}}{\pi}U_2 = 1,35U_2$$

som betyr at likespenningens høyeste verdi vil være

$$U_{di0\ \max} = 1,35 \cdot \frac{1500}{22000} \cdot 23500 = 2160\,\mathrm{V}$$

og dens laveste verdi vil være

$$U_{di0\ \min} = 1,35 \cdot \frac{1500}{22000} \cdot 21000 = 1930\,\mathrm{V}$$

Kommuteringsspenningsfallet vil være

$$U_{dx} = \frac{3X_t I_d}{\pi} = \frac{3 \cdot 1,5 \cdot 100}{\pi} = 143\,\mathrm{V}$$

Formel (6.29) definerer en styrt likespenning:

$$U_d = U_{di0}\frac{1 + \cos\alpha}{2} - U_{dx}$$

$$\cos\alpha = 2\frac{U_d + U_{dx}}{U_{di0}} - 1$$

Denne kan løses med hensyn på $\cos\alpha$ og α:

$$\begin{aligned} \cos\alpha &= 2\frac{U_d + U_{dx}}{U_{di0}} - 1 \\ \alpha &= \arccos\left(2\frac{U_d + U_{dx}}{U_{di0}} - 1\right) \end{aligned}$$

Ved en nettspenning på 23,5kV må styrevinkelen være

$$\alpha = \arccos\left(2\frac{1500 + 143}{2160} - 1\right) = 58,6\,^\circ$$

Ved en nettspenning på 21kV må styrevinkelen være

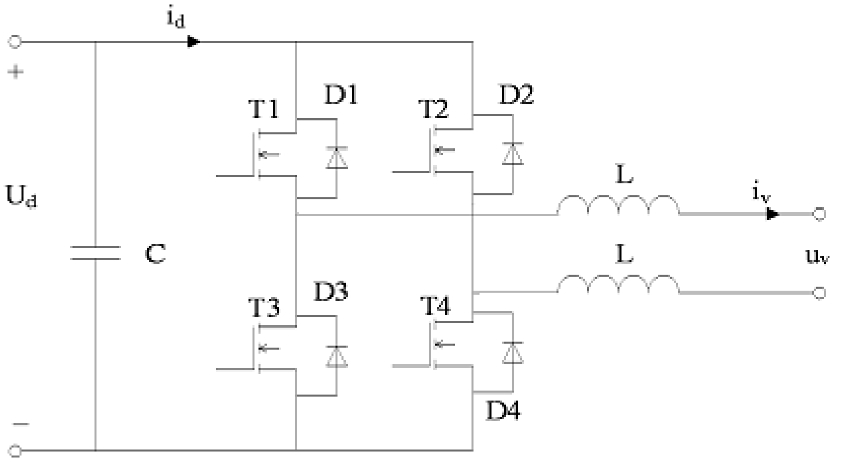
$$\alpha = \arccos\left(2\frac{1500 + 143}{1930} - 1\right) = 45,4\,^\circ$$

Høyeste sperrespenning gitt ved

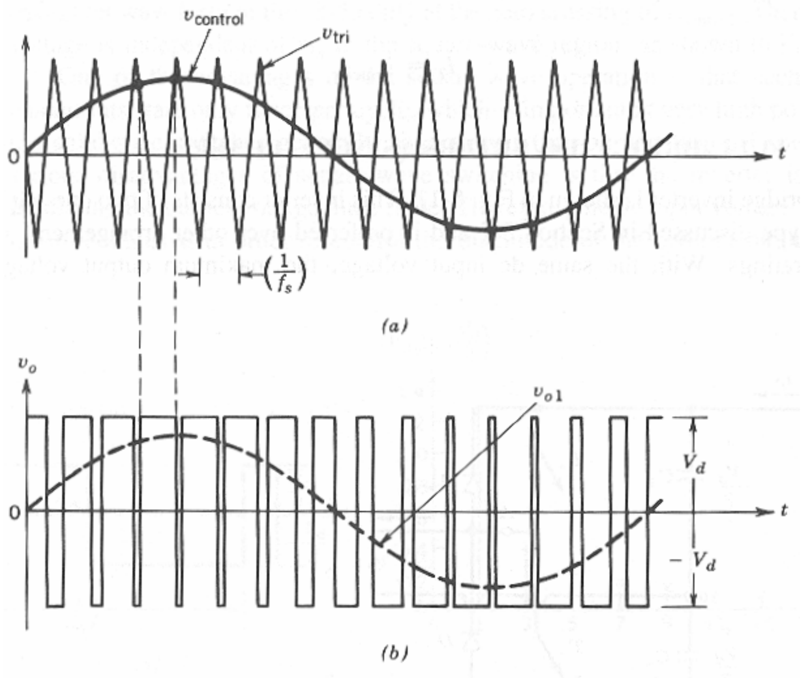
$$U_{s\ \max} = \sqrt{2}U_2 = \sqrt{2} \cdot \frac{1500}{22000} \cdot 23500 = 2,27\,\mathrm{kV}$$

6.6 Aktive strømrettere

En helt annen type styrte strømrettere er aktive strømrettere (switch mode converters). Disse benytter raske halvlederkomponenter som kan bryte strømmen mens de er strømførende. Disse strømretterne genererer vekselspenning ved å pulsbreddemodulere en likespenning, slik det er vist på figur 6.21.
Vi skal nå se nærmere på to kretser som baserer på en slik pulsbreddemodulasjon, og vanligvis er disse aktive strømretterne spenningsmatet. Figur 6.20 viser en enfase aktiv vekselretter, og figur 6.21 viser utgangsspenningens momentanverdi (heltrukken linje), og den grunnharmoniske (stiplet linje).
På grunn av friløpsdiodene D1 - D4 kan strømmen gå begge veier gjennom omformeren, som med andre ord kan operere både som likeretter og vekselretter.



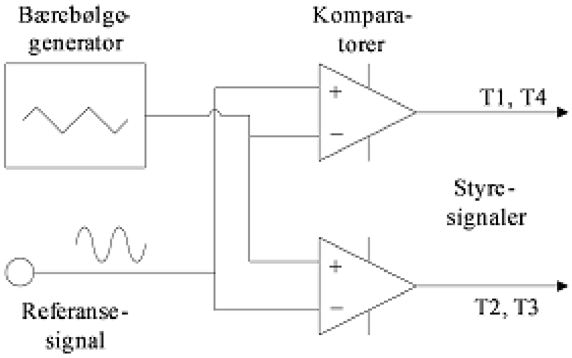
Figur 6.20: Enfase spenningsmatet aktiv vekselretter med glattespoler



Figur 6.21: Kontrollsignal og utgangsspenning for enfase aktiv vekselretter

Når utgangsspenningen har positiv verdi, leder transistorene T1 og T4. Dermed vil den øvre vekselspenningsterminalen være tilkoblet plusspolen og den nedre være tilkoblet minuspolen på likespenningskilden. Når utgangsspenningen har negativ verdi, leder transistorene T2 og T3. Da vil den øvre vekselspenningsterminalen være tilkoblet minuspolen og den nedre være tilkoblet plusspolen.

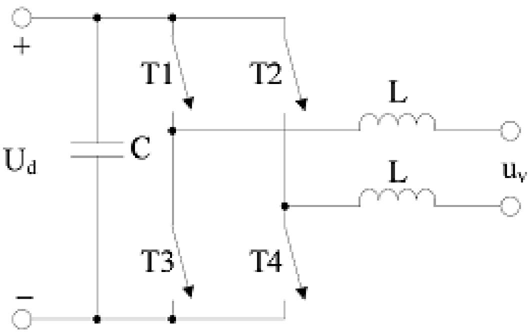
Friløpsdiodene D1 – D4 gir likestrømmen fri passasje dersom det er behov for det. Dette beskytter transistorene mot skadelige overspenninger. Glattekondensatoren C sørger for at likespenningen er mest mulig glatt. Dermed har vi en spenningsmatet krets. Filterspolene L har to formål: For det første danner de en buffer mellom den pulsbreddemodulerte likespenningen på figur 6.21 og en mer sinusformet lastspenning. Dessuten reduserer de mengden av svitsjerippel på vekselstrømmen. Det er vanlig å benytte svitsjefrekvenser fra $10 - 100\ \mathrm{kHz}$.
De fire transistorene T1 – T4 mottar kontrollsignaler fra en kontrollkrets som er vist på figur 6.22.



Figur 6.22: Kontrollkrets for aktiv strømretter

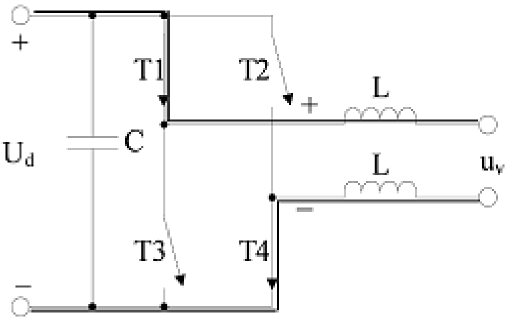
De to operasjonsforsterkerne (komparatorene) vil gi ut et høyt signal når potensialet på plussinngangen er høyere enn på minusinngangen, og et lavt signal når det omvendte er tilfelle. Dermed vil T1 og T4 lede så lenge referansesignalet ligger høyere enn triangelsignalet (bærebølgen), og T2 og T3 vil lede dersom triangelsignalet ligger høyest. På denne måten oppnås spenningskurvene som er vist på figur 6.21. Forutsetningen er at referansesignalet ikke har høyere amplitude enn bærebølgen. I så fall vil pulsene smelte mer og mer over i hverandre, og blir referansesignalet høyt nok, vil kretsen gi ut en lavfrekvent frikantspenning. Dersom referansesignalet er høyere enn bærebølgen, er signalet overmodulert. I fortsettelsen forutsetter vi at kretsen opererer i normalt arbeidsområde, altså uten overmodulasjon.

Figur 6.23 viser en såkalt H-bru som i dette tilfelle opererer som vekselretter og som styres med pulsbreddemodulerte spenninger. Omformerspenningen u_v veksler mellom U_d og $-U_d$.

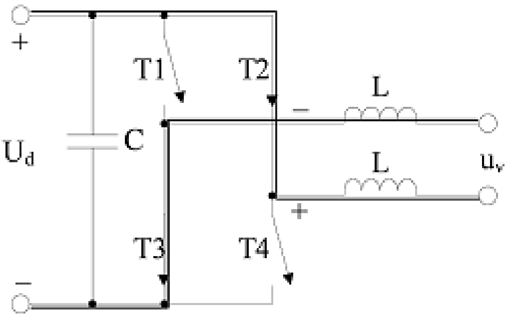


Figur 6.23: Enfase vekselretter med pulsbreddemodulering

På figur 6.24 er $u_v = U_d$, mens figur 6.25 viser et tilfelle hvor $u_v = -U_d$.

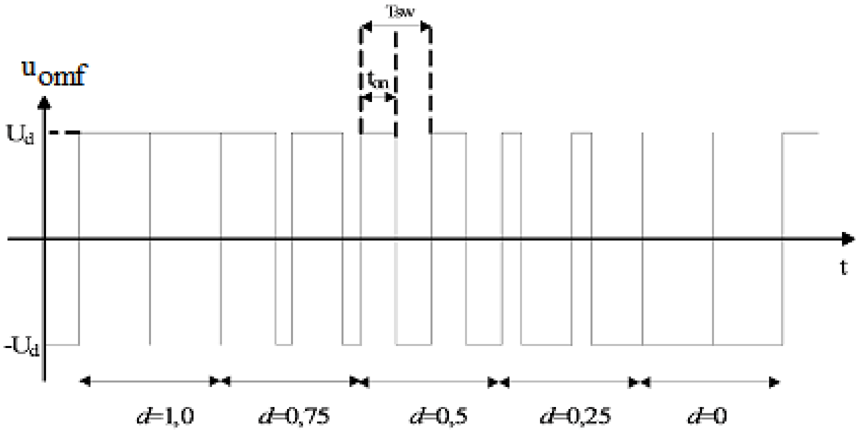


Figur 6.24: Positiv utgangsspenning; T1 og T4 leder



Figur 6.25: Negativ utgangsspenning; T2 og T3 leder

Utgangsspenningen fra omformeren har altså bare to nivåer, U_d eller $-U_d$. Middelverdien av u_v kan imidlertid være hva som helst mellom disse to ytterpunktene, avhengig av hvor lenge spenningen går i den ene eller den andre retningen.
Periodetiden til trekantsignalet kalles svitsjeperioden og betegnes T_{sw}. Denne er konstant og bestemmes av frekvensen til trekantsignalet, som samsvarer med svitsjefrekvensen. Den tiden utgangssignalet går høyt ($u_v = U_d$), kalles på-tiden og benevnes t_{on}. Forholdet mellom pulsbredden og svitsjefrekvensens periodetid, kalles pulsforhold (duty cycle), og symbolet d benyttes. Dette forholdet er gitt i formel (6.30). Figur 6.26 viser ulike pulsforhold for vekselspenningens utgangsspenning.



Figur 6.26: Sammenheng mellom utgangsspenning og pulsforhold for aktiv vekselretter

Dersom $d = 1,0$, vil utgangsspenningens middelverdi være lik likespenningen: $u_v = U_d$. Dersom $d = 0$, vil utgangsspenningens middelverdi være lik likespenningen med omvendt polaritet: $u_v = -U_d$.

$$d = \frac{t_{on}}{T_{sw}} \tag{6.30}$$

Pulsforholdet kan også uttrykkes ved hjelp av styrespenningene:

$$d = \frac{1}{2} + \frac{u_{control}}{2U_{tri}} \tag{6.31}$$

hvor $u_{control}$ er øyeblikksverdien av styrespenningen og U_{tri} er amplitudeverdien av trekantspenningen.

Denne sammenhengen er ikke like lett å se, men det blir klarere hvis man setter inn noen talleksempler. Dersom $u_{control} = U_{tri}$, altså toppverdien av trekantsignalet, vil på-tiden fylle hele periodetiden, og da må $d = 1,0$. Setter man inn $u_{control} = U_{tri}$ i (6.31), blir $d = 1,0$. Tilsvarende bør $d = 0,5$ hvis $u_{control} = 0$, og det forventes at $d = 0$ for $u_{control} = -U_{tri}$. Dette stemmer også.

Som før nevnt har utgangsspenningen bare to nivåer, men en antar at øyeblikksverdien av u_{conv} tilsvarer middelverdien av det pulsbreddemodulerte signalet. Da vil sammenhengen mellom likespenning, pulsforhold og øyeblikksverdien av vekselspenningen være gitt ved

$$u_{omf} = U_d \left(2d - 1\right) \tag{6.32}$$

Dette kan også etterprøves. For $d = 1,0$ forventes at $u_v = U_d$. Dette samsvarer med (6.32). Ved $d = 0,5$ bør $u_v = 0$, og ved $d = 0$ bør $u_v = -U_d$. Dette stemmer også med (6.32), som angir øyeblikksverdien av vekselspenningen for hvilken som helst styrespenning. Dersom styrespenningen er sinusformet, kan den skrives som

$$u_{control} = U_{m,control} \sin \omega t \tag{6.33}$$

hvor $U_{m,control}$ er styresignalets amplitude. Dersom en setter amplitudeverdien av $u_{control}$ inn i (6.31), får en et uttrykk for maksimal utstyring:

$$d_{\max} = \frac{1}{2} + \frac{U_{m,control}}{2U_{tri}} \tag{6.34}$$

Hvis en setter dette inn i (6.32), får en et uttrykk for vekselspenningens amplitudeverdi U_m:

$$U_m = U_d \left(2d_{\max} - 1\right) \tag{6.35}$$

Siden effektivverdien for et sinusformet signal er roten av 2 ganger lavere enn amplitudeverdien, kan omformerspenningens effektivverdi skrives som

$$U_{omf} = \frac{U_d \left(2d_{\max} - 1\right)}{\sqrt{2}} \tag{6.36}$$

Dersom en setter (6.34) inn i (6.36), gis omformerspenningen U_{conv} som en funksjon av styrespenningens effektivverdi $U_{control}$:

$$U_{omf} = U_d \left(2\left(\frac{1}{2} + \frac{U_{control}}{2U_{tri}}\right) - 1\right) = U_d \frac{U_{control}}{U_{tri}} \tag{6.37}$$

Eksempel 8 *Omformeren på figur 6.23 har en likespenning* $U_d = 100\,\mathrm{V}$. *Trekantspenningen har en amplitude* $U_{tri} = 5,0\,\mathrm{V}$ *og en frekvens* $f_{sw} = 10\,\mathrm{kHz}$. *Styresignalet har en effektivverdi* $U_{control} = 3,0\,\mathrm{V}$. *Regn ut svitsjeperioden, lengste og korteste på-tid, samt vekselretterspenningen* U_{omf}.

Løsning:
Svisjeperioden er gitt ved

$$T_{sw} = \frac{1}{f_{sw}} = \frac{1}{10000} = 100\,\mu\mathrm{s}$$

Høyeste og laveste pulsforhold er

$$\begin{aligned} d_{\max} &= \frac{1}{2} + \frac{U_{m,control}}{2U_{tri}} = \frac{1}{2} + \frac{\sqrt{2}U_{control}}{2U_{tri}} = \frac{1}{2} + \frac{\sqrt{2}\cdot 3,0}{2\cdot 5,0} = 0,924 \\ d_{\min} &= \frac{1}{2} + \frac{-U_{m,control}}{2U_{tri}} = \frac{1}{2} - \frac{\sqrt{2}U_{control}}{2U_{tri}} = \frac{1}{2} - \frac{\sqrt{2}\cdot 3,0}{2\cdot 5,0} = 0,076 \end{aligned}$$

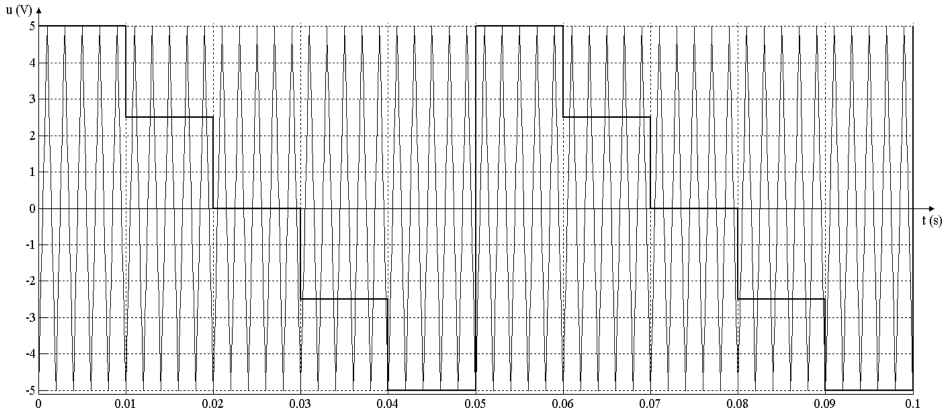
Lengste og korteste på-tid er

$$\begin{aligned} t_{on,\max} &= T_{sw}\cdot d_{\max} = 100\,\mu\mathrm{s}\cdot 0,924 = 92,4\,\mu\mathrm{s} \\ t_{on,\min} &= T_{sw}\cdot d_{\min} = 100\,\mu\mathrm{s}\cdot 0,076 = 7,6\,\mu\mathrm{s} \end{aligned}$$

Vekselretterspenningen er

$$U_{omf} = U_d\frac{U_{control}}{U_{tri}} = 100\cdot\frac{3,0}{5,0} = 60\,\mathrm{V}$$

Eksempel 9 *Figur 6.27 viser et referansesignal med fem signalnivåer, samt et triangelsignal. Bestem triangelsignalets periodetid, samt omformerens svitsjefrekvens. Bestem dessuten pulsforholdet for de fem ulike signalnivåene. Likespenningen har en verdi* $U_d = 100\,\mathrm{V}$. *Tegn triangelsignalet, styresignalet, den pulsbreddemodulerte utgangsspenningen, samt middelverdien av denne i felles plott.*

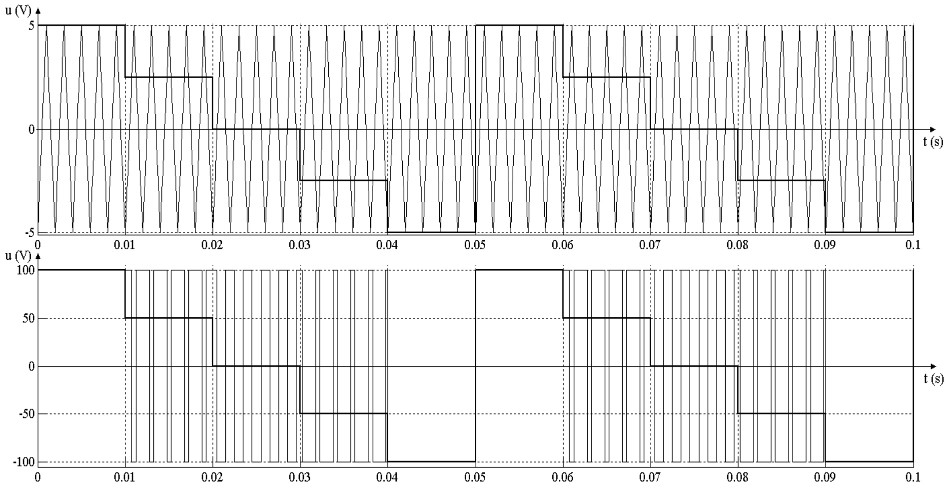


Figur 6.27: Triangelspenning med referansesignal

Løsning:
Triangelsignalet har en periodetid på $2,0\,\mathrm{ms}$. Det gir en svitsjefrekvens

$$f_{sv} = \frac{1}{T} = \frac{1}{0,002} = 500\,\mathrm{Hz}$$

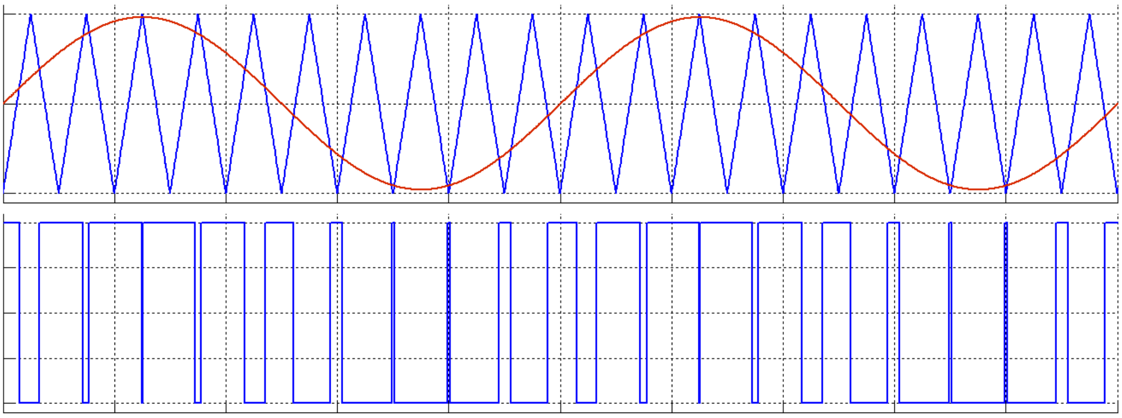
Ved høyeste styrespenning $(5,0\,\mathrm{V})$ er på-tiden like lang som svitsjeperioden : $d = 1,0$. Ved styrespenning $2,5\,\mathrm{V}$ er på-tiden 75% av periodetiden, og dermed er $d = 0,75$. Ved $u_{ref} = 0\,\mathrm{V}$ er $d = 0,5$, ved $u_{ref} = -2,5\,\mathrm{V}$ er $d = 0,25$, og ved $u_{ref} = -5,0\,\mathrm{V}$ er $d = 0$. Figur 6.28 viser sammenhengen mellom referansesignal, triangelsignal, pulsbreddemodulert utgangsspenning og midlere utgangsspenning. En ser at referansesignalet (kontrollsignalet) og midlere utgangsspenning er sammenfallende.



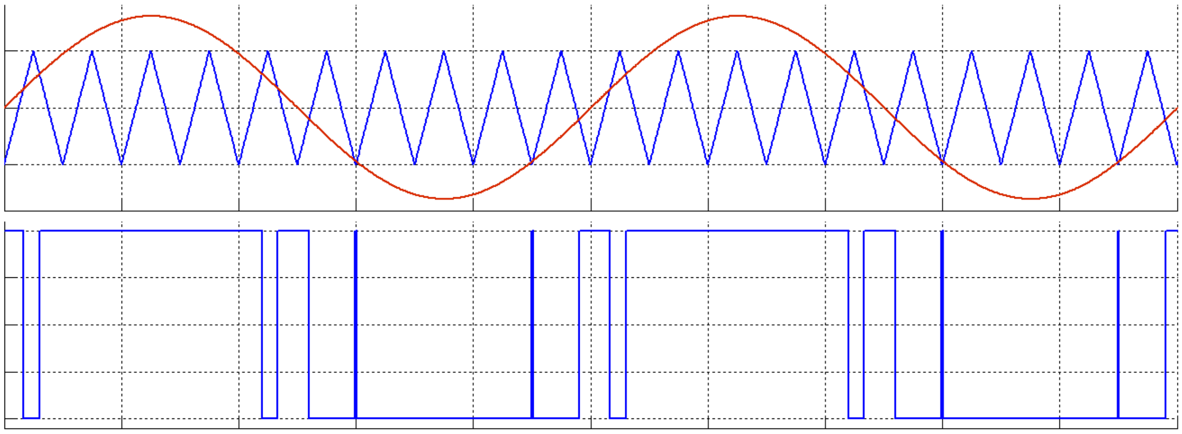
Figur 6.28: Kontrollsignaler (øverst) og utgangsspenning (nederst)

6.7 Overmodulasjon

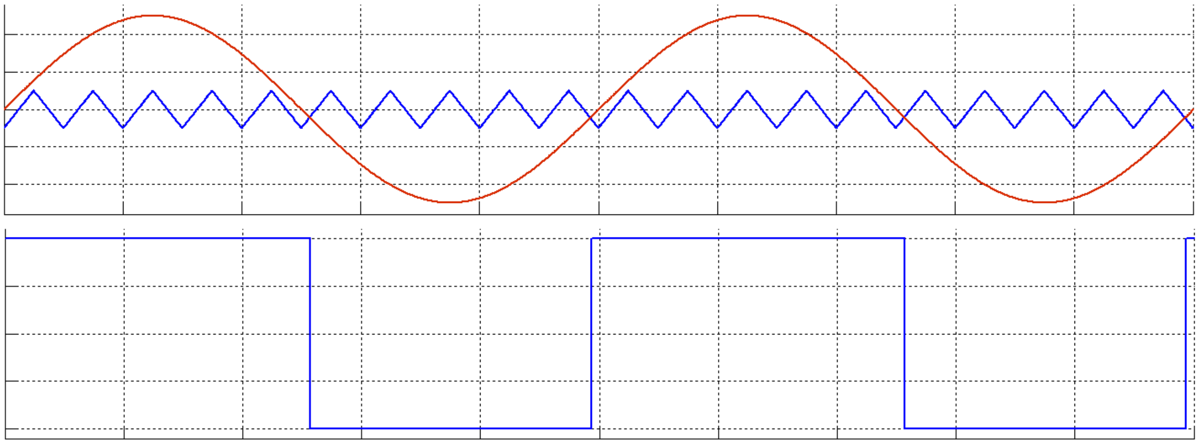
Figur 6.29 viser styre- og utgangsspenninger når referansespenningen ikke overskrider triangelspenningen. Utgansspenningen vil følge referansespenningen. Figur 6.30 viser derimot et tilfelle der referansespenningen overskrider triangelspenningen med 50% (overmodulasjon), og resultatet er at den pulsbreddemodulerte spenningen ligger på U_d eller $-U_d$ i lange perioder. Utgangsspenningen følger ikke lenger inngangsspenningen. Ved kraftig overmodulasjon, som vist på figur 6.31, vil utgangsspenningen mer og mer gå mot en nettfrekvent firkantpuls, og referansesignalet vil ikke lenger ha noen innvirkning på utgangssignalet. Dette fremkommer også av figur 6.32. Det lineære området ender ved $0,71U_d$.



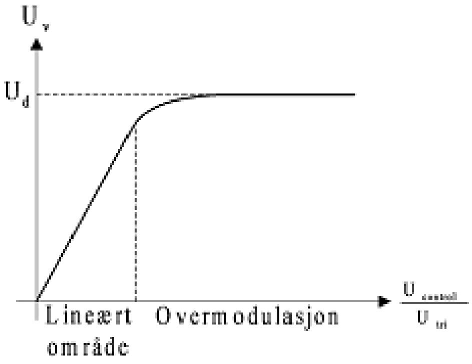
Figur 6.29: Styre- og utgangssignaler ved normal pulsbreddemodulasjon



Figur 6.30: Styre- og utgangssignaler ved moderat overmodulasjon



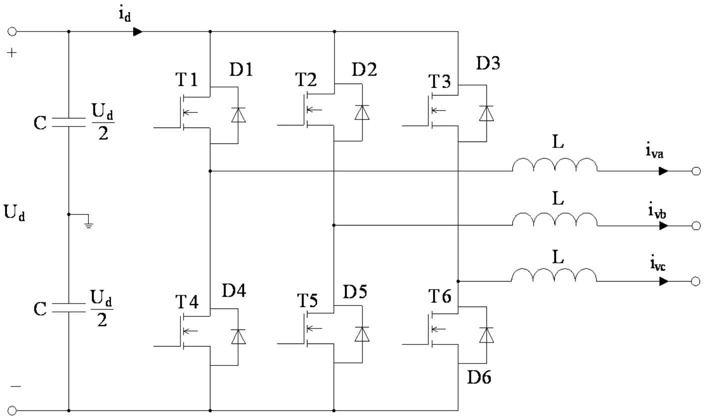
Figur 6.31: Styre- og utgangssignaler ved kraftig overmodulasjon



Figur 6.32: Sammenheng mellom pulsforhold og vekselspenning

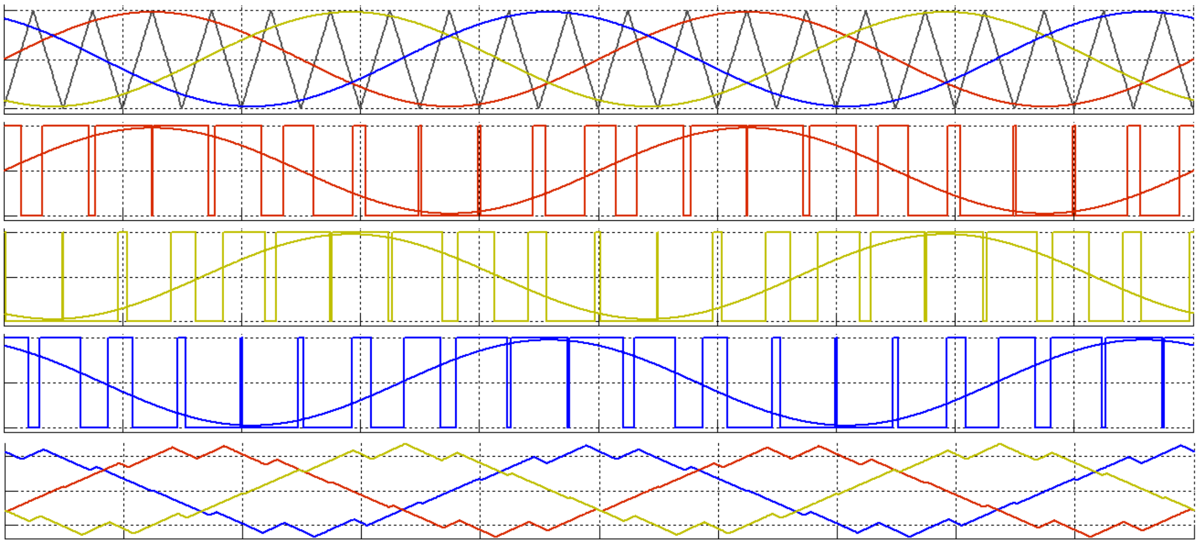
6.8 Trefaseomformere

Kretsen på figur 6.20 finnes også i trefaseutførelse. En slik trefase vekselretter er vist på figur 6.33. Den har mange fellestrekk med enfaseutførelsen, og hver av fasespenningene styres på samme måte som for enfaseomformeren. Det betyr at kretsen krever tre slike kontrollspenninger som er beskrevet på figur 6.22. Den første styrer T1 og T4, den neste styrer T2 og T5, og den tredje styrer T3 og T6. De tre referansesignalene er 120° faseforskjøvet. Slik oppnår man at omformeren gir ut roterende trefasespenninger. De tre kontrollkretsene mottar et felles bærebølgesignal. Derved oppnås en synkronisert svitsjing i de tre fasene, og mengden av overharmoniske strømkomponenter reduseres.



Figur 6.33: Trefase spenningsmatet aktiv vekselretter med glattespoler

Figur 6.34 viser kontrollsignalene (øverst), pulsbreddemodulerte spenninger og middelspenninger for fase L1, L2 og L3, og linjestrømmene (nederst).



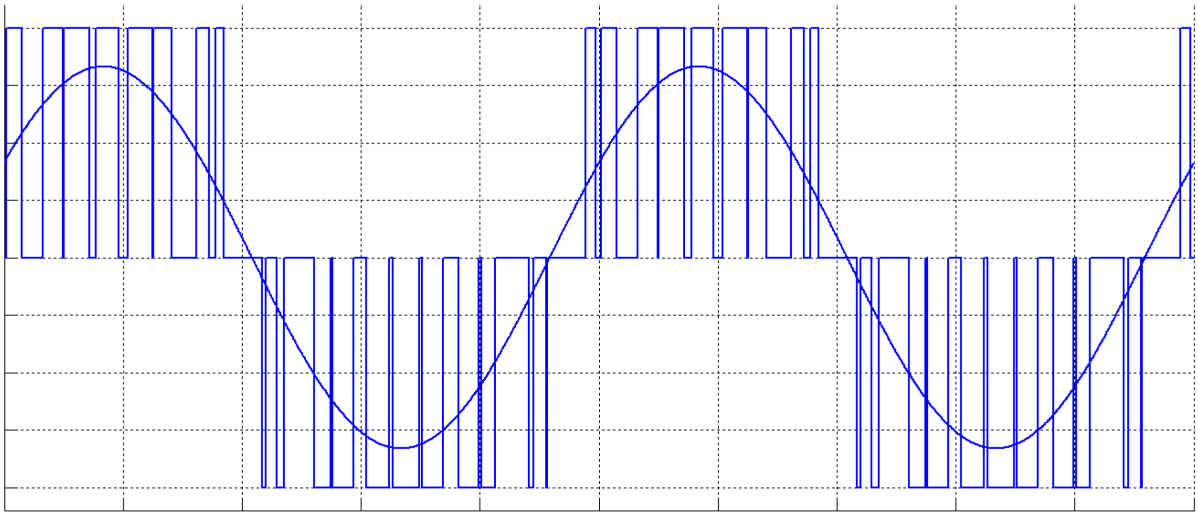
Figur 6.34: Spenninger og strømmer ved trefase pulsbreddemodulering

Figur 6.35 viser vekselretterens linjespenning mellom fase L1 og L2.
Formel 6.37 viser utgangsspenningen for en enfase vekselretter. Fasespenningen ut av en trefase vekselretter vil være gitt ved

$$U_{conv,f} = \frac{U_{control}}{2U_{tri}} U_d \qquad (6.38)$$

Linjespenningen U_{conv} blir da

$$U_{conv} = \frac{\sqrt{3}}{2} \frac{U_{control}}{U_{tri}} U_d \qquad (6.39)$$



Figur 6.35: Linjespenning mellom fase L1 og L2

Ser en bort fra spenningsrippelet på utgangen av vekselretteren, kan den betraktes som en trefase spenningskilde med sinusformede spenninger. Dersom vekselretteren forsyner nettet, vil kretsen bestå av to sammenkoblede spenningskilder, som vist på figur 6.36. Retningen på effektflyten vil avhenge av spenningenes amplitude og fase.

Eksempel 10 *En aktiv strømretter er tilkoblet et* $400\,\mathrm{V}$ $50\,\mathrm{Hz}$ *lavspentnett gjennom* $10\,\mathrm{mH}$ *glattespoler og en linje med en impedans på* $(100 + j500)\ \mathrm{m\Omega}$*. Omformerspenningen per fase er* $240\,\mathrm{V}\angle 35\,^\circ$*, og fasespenningen i transformatoren er* $230\,\mathrm{V}\angle 0\,^\circ$*. Beregn aktiv og reaktiv effektflyt.*

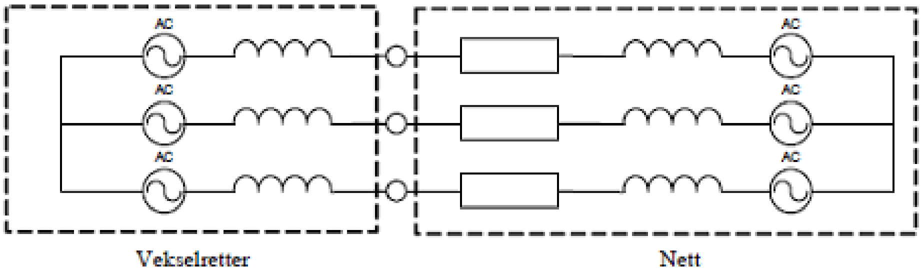
Løsning:
Glattespolene har en reaktans $X_L = 2\pi f L = 2\pi \cdot 50 \cdot 0.01 = 3.14\,\Omega$.

Total impedans i overføringen blir $\overrightarrow{Z} = j3.14 + (0.1 + j0.5) = (0.1 + j3.64)\,\Omega$.

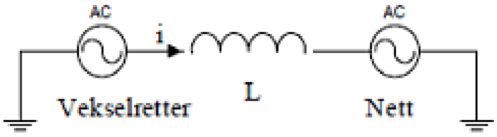
Spenningsfallet over overføringen blir $\overrightarrow{\Delta U} = \overrightarrow{U}_{omf} - \overrightarrow{U}_v = 240\,\mathrm{V}\angle 35\,^\circ - 230\,\mathrm{V}\angle 0\,^\circ = 142\,\mathrm{V}\angle 104\,^\circ$.

Det gir følgende linjestrøm: $\overrightarrow{I} = \frac{\overrightarrow{\Delta U}}{\overrightarrow{Z}} = \frac{142\angle 104\,^\circ}{0.1+j3.64} = 39\,\mathrm{A}\angle 15.6\,^\circ$

Effektflyten inn eller ut av transformatoren blir da $\overrightarrow{S} = 3 \cdot \overrightarrow{U}_v \cdot \overrightarrow{I}^* = 3 \cdot 230 \cdot 39\angle -15.6 = (25,9 - j7.2)\ \mathrm{kV\,A}$, som forteller at omformeren leverer $25,9\,\mathrm{kW}$ aktiv effekt, men samtidig trekker $7,2\,\mathrm{kV\,Ar}$ reaktiv effekt.



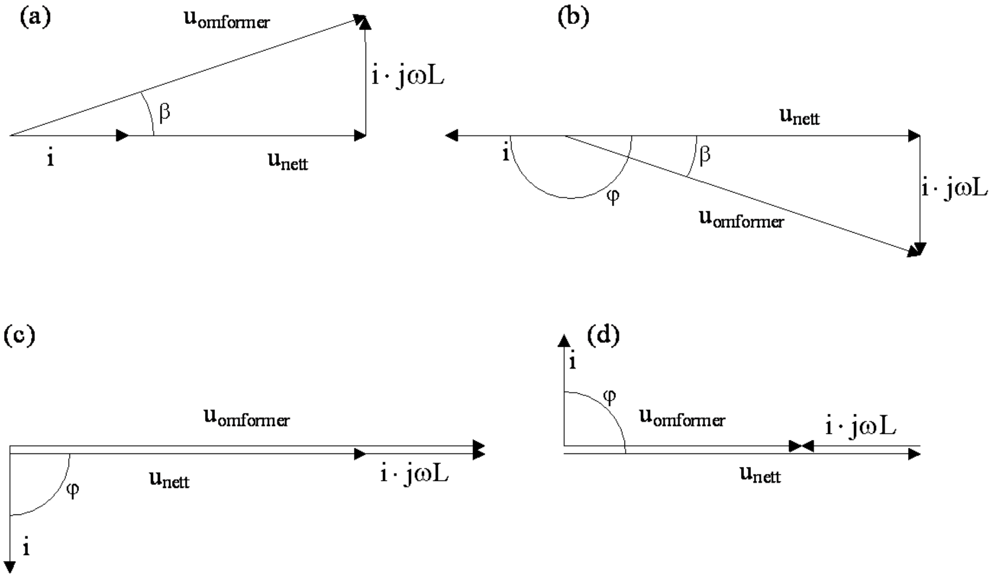
Figur 6.36: Ekvivalentskjema for aktiv vekselretter tilkoblet nettet



Figur 6.37: Faseekvivalent for nettilkoblet vekselretter

Reaktansene i nettet er vanligvis så mye høyere enn resistansene, at sistnevnte ofte neglisjeres. I så fall kan en slå sammen reaktansene, og faseekvivalenten ser ut som på figur 6.37.

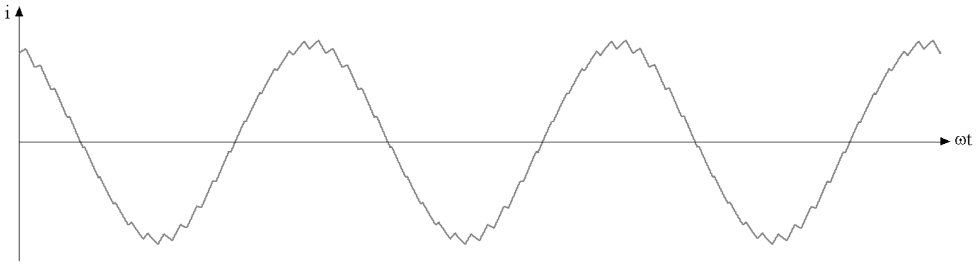
Figur 6.38 viser fire ulike driftssituasjoner. På figur 6.38a er strøm og spenning i fase, og omformeren leverer aktiv effekt til nettet. Den går i vekselretterdrift og effektfaktoren $\cos\varphi = 1,0$. I tilfelle (b) er strøm og spenning i motfase, noe som betyr at omformeren går i likeretterdrift og dermed mottar aktiv effekt fra nettet. Effektfaktoren er fortsatt $\cos\varphi = 1,0$.



Figur 6.38: Ulike driftssituasjoner for nettilkoblet vekselretter

I tilfelle (c) ligger strømmen 90° etter spenningen, og omformeren leverer reaktiv effekt til nettet. I tilfelle (d) ligger strømmen 90° foran spenningen, og omformeren bruker reaktiv effekt. I begge de siste tilfellene er $\cos\varphi = 0$. Omformeren kan altså drives både som like- og vekselretter, og den kan brukes som fasekompensator.

I de foregående betraktningene har vi antatt at vekselretterens utgangsspenning er sinusformet. Som kjent er den i virkeligheten en pulserende likespenning, som vist på figur 6.21. Dermed vil ikke vekselretterens linjestrømmer være helt sinusformede, men inneholde en viss mengde svitsjerippel, slik det er vist på figur 6.39.



Figur 6.39: Linjestrøm med svitsjerippel

To forhold vil være avgjørende for hvor mye rippel strømmene inneholder: Svitsjefrekvensen og størrelsen på induktansene L. En høy svitsjefrekvens gir lavt rippel, men høye dynamiske svitsjetap. En høy induktansverdi gir også lavt svitsjerippel, men setter større begrensninger for hvor mye vekselretterspenningen kan variere. Uforholdsmessig høye induktanser gir også en risiko for skadelige overspenninger dersom et plutselig strømbrudd skulle inntreffe i kretsen. Størrelsen på strømrippelet er altså en avveining mellom god strømkvalitet og gode driftsbetingelser for omformeren. Maksimalt strømrippel er gitt ved formel (6.40).

$$I_{rippel} = \frac{U_d}{L \cdot f_{sw}} \tag{6.40}$$

Eksempel 11 *Et solcelleanlegg på* $10\ \mathrm{kW}$ *og* $350\ \mathrm{V}$ *er knyttet til nettet ved hjelp av en aktiv trefase vekselretter med en svitsjefrekvens på* $20\ \mathrm{kHz}$*. De totale svitsjetapene utgjør* $400\ \mathrm{W}$*. Nettspenningen er* $230\ \mathrm{V}$ *med en frekvens på* $50\ \mathrm{Hz}$*. Beregn vekselretterens strøm når solcelleanlegget leverer nominell effekt ved* $\cos\varphi = 1,0$*. Rippelstrømmen skal ikke overstige* 5 *% av merkestrømmen. Hvor store må induktansene være? Beregn vekselrettens spenning (størrelse og fasevinkel referert nettspenningen) ved merkedrift.*

Løsning:
Levert effekt til nettet blir

$$P_{ut} = P_{sol} - \Delta P = 10000 - 400 = 9,6\,\mathrm{kW}$$

Effekten i et trefasesystem er gitt ved

$$P = \sqrt{3} \cdot U \cdot I \cdot \cos\varphi$$

Det gir følgende merkestrøm:

$$I = \frac{P_{ut}}{\sqrt{3} \cdot U \cdot \cos\varphi} = \frac{9600}{\sqrt{3} \cdot 230} = 24,1\,\mathrm{A}$$

Maksimal tillatt strømrippel blir da

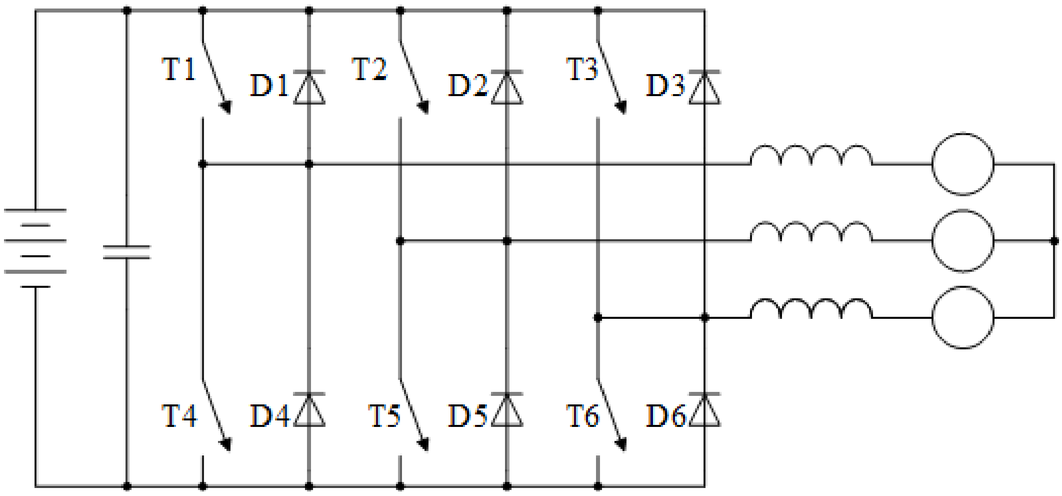
$$I_{rippel} = 0,05I = 0,05 \cdot 24,1 = 1,21\,\mathrm{A}$$

Induktansene må da ha en minimumsverdi

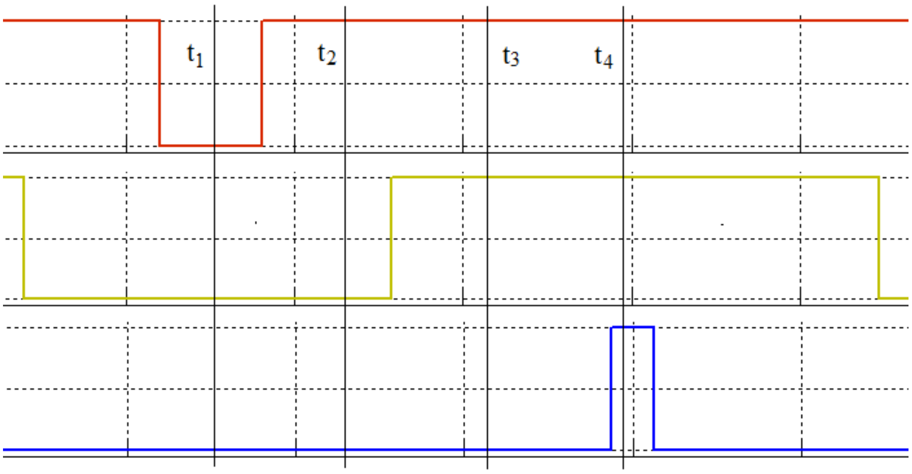
$$L = \frac{U_d}{I_{rippel} \cdot f_{sw}} = \frac{350}{1,21 \cdot 20000} = 14,5\,\mathrm{mH}$$

Det fremgår av figur 6.38a at omformerspenningen må ha en reell komponent lik nettspenningen (faseverdi) og en imaginær komponent lik $X \cdot I$. Omformerens spenning blir da

$$\begin{aligned}
U_{omformer,fase} &= \frac{230}{\sqrt{3}} + j\omega L \cdot I = 132,8 + j2\pi f L \cdot I \\
&= 132,8 + j2\pi \cdot 50 \cdot 0,0145 \cdot 24,1 = (132,8 + j109,8)\ \mathrm{V} \\
U_{omformer,fase} &= 172,4\,\mathrm{V}\angle 39,6\,^{\circ} \\
U_{omformer} &= 298,6\,\mathrm{V}\angle 39,6\,^{\circ}
\end{aligned}$$



Figur 6.40: Aktiv trefase omformer tilkoblet nettet



Figur 6.41: Øyeblikksverdier av utgangsspenninger i fase L1 (rød), L2 (grønn) og L3 (blå).

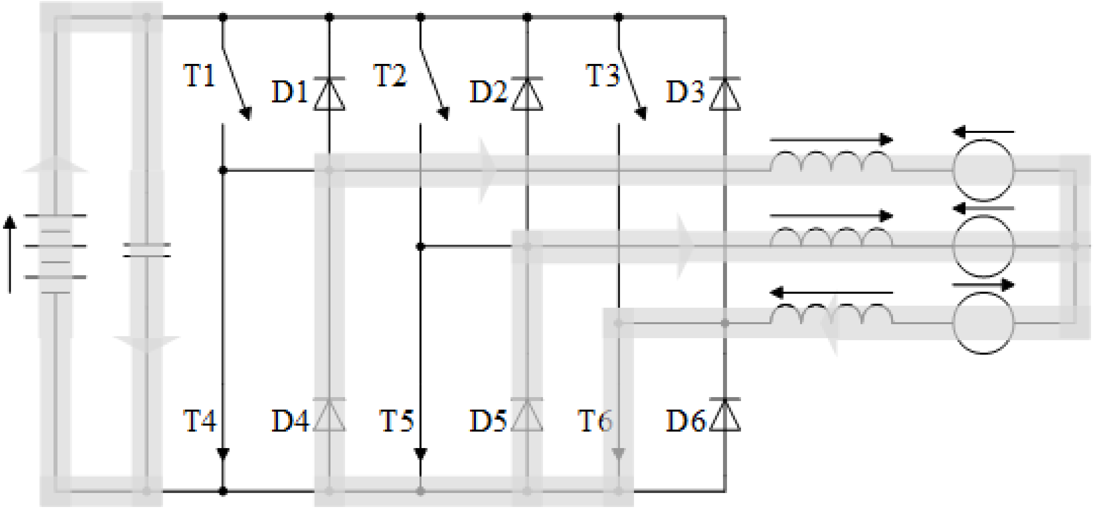
6.9 Effektretning

En aktiv trefase omformer som vist på figur 6.40 har tre greiner, en for hver fase, og hver grein har to mulige tilstander. Det betyr at transistorene kan stå i åtte mulige posisjoner. Hver fase kan ha strøm inn i omformeren, ut av omformeren, eller fasen kan være strømløs, ved nullgjennomgang. Det betyr at strømflyten kan ha tjuesju ulike tilstander. Omformeren kan altså befinne seg i 216 ulike tilstander. Vi skal ta et snapshot"av et bestemt øyeblikk, vist på figur 6.41.
En ser av figuren at L1 ligger på en høy positiv verdi (lang på-tid), L2 ligger litt over null, mens L3 er nær negativt maksimum. Det er fire mulige transistortilstander: Ved tidspunkt t_1 leder T4, T5 og T6. Ved t_2 skifter den første greina fra T4 til T1 mens de andre forblir uendret. Ved t_3 skifter den andre greina fra T5 til T2, og ved t_4 ligger alle fasene høyt (T1, T2 og T3 leder). I løpet av resten av svitsjeperioden skifter omformeren tilbake igjen. Disse skiftingene skjer noen tusen ganger i løpet av et sekund.

For enkelthets skyld antar vi at lastflyten har $\cos\varphi = 1,0$, det vil si at linjestrømmen i L1 er positiv, linjestrømmen i L2 er lav, men også positiv, mens linjestrømmen i L3 er negativ. I løpet av det korte tidsintervallet vi undersøker, kan vi betrakte både nettspenninger og linjestrømmer som tilnærmet konstante. Vi vil videre undersøke hvordan strømmene flyter i de fire tidspunktene t_1 - t_4, både ved vekselretter- og likeretterdrift.

Omformeren som vekselretter
I fase L1 og L2 går det strømmer ut av omformeren, mens strømmen er negativ i L3 og følgelig flyter inn i omformeren.

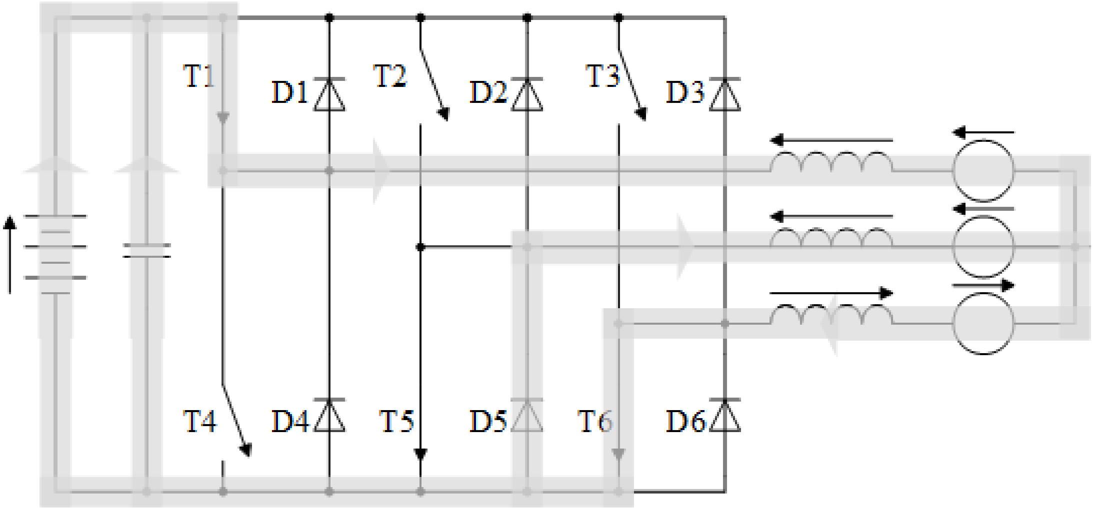
Tidspunkt t_1 (T4, T5 og T6 leder)



Figur 6.42: Vekselretterdrift ved tidspunkt t_1

En ser av figur 6.42 at DC- og AC-siden er atskilt. DC-kilden lader opp kondensatoren. T6 leder, mens returstrømmen går gjennom friløpsdiodene D4 og D5. Dette skyldes at transistorene bare kan lede strøm i en retning. Nettspenningene virker i motsatt retning av strømmene, og disse vil derfor falle. Induktansene genererer spenninger som forsøker å opprettholde strømmene.

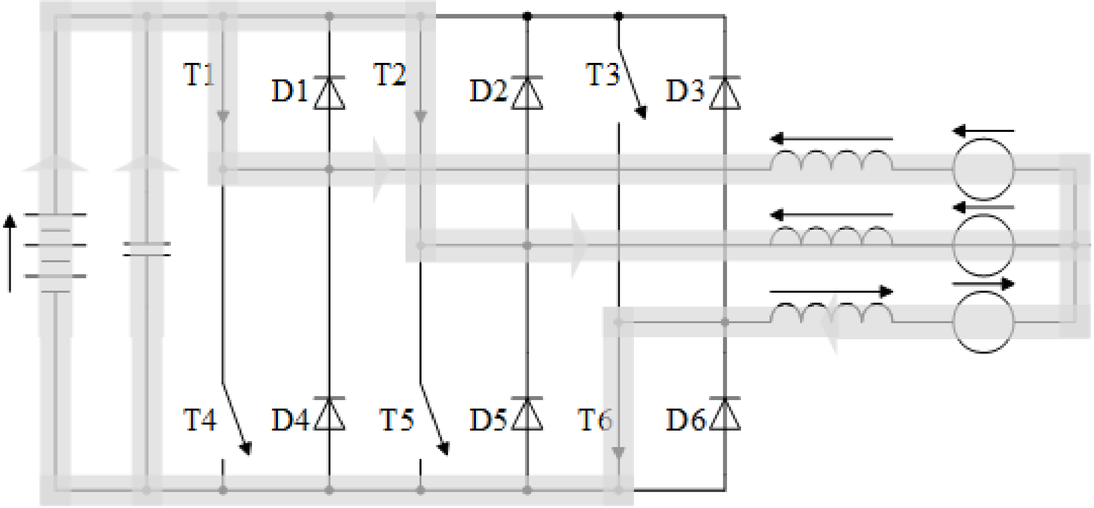
Tidspunkt t_2 (T1, T5 og T6 leder)



Figur 6.43: Vekselretterdrift ved tidspunkt t_2

Som det fremgår av figur 6.43, danner T1 forbindelse mellom DC- og AC-siden. Både DC-kilden og kondensatoren gir sine strøm-bidrag til vekselretteren. DC-kretsen får AC-strømmene til å øke, og derfor endrer spenningene over induktansene retning.

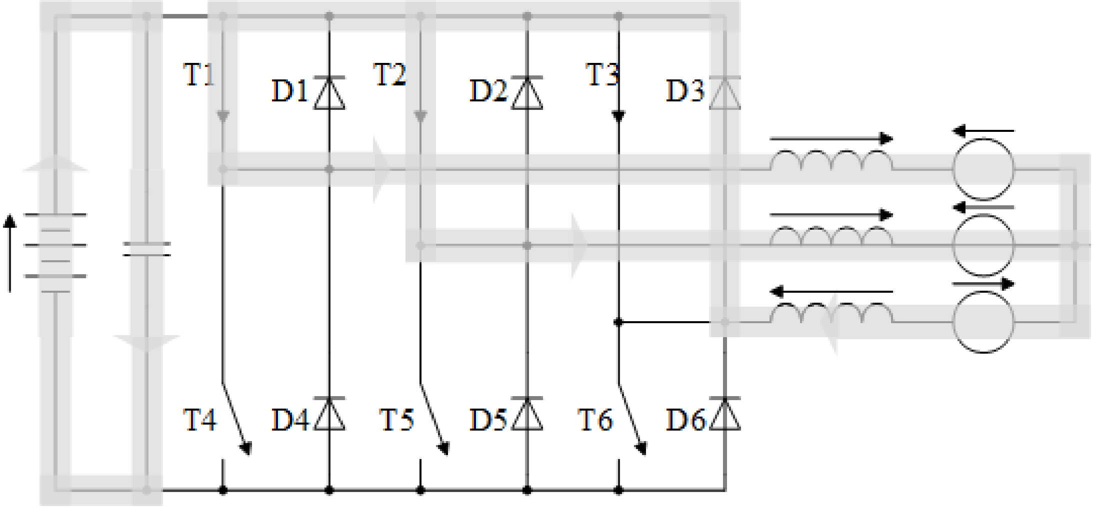
Tidspunkt t_3 (T1, T2 og T6 leder)



Figur 6.44: Vekselretterdrift ved tidspunkt t_3

Figur 6.44 viser omtrent samme driftssituasjon som figur 6.43, bortsett fra at ingen friløpsdioder er i funksjon.

Tidspunkt t_4 (T1, T2 og T3 leder)



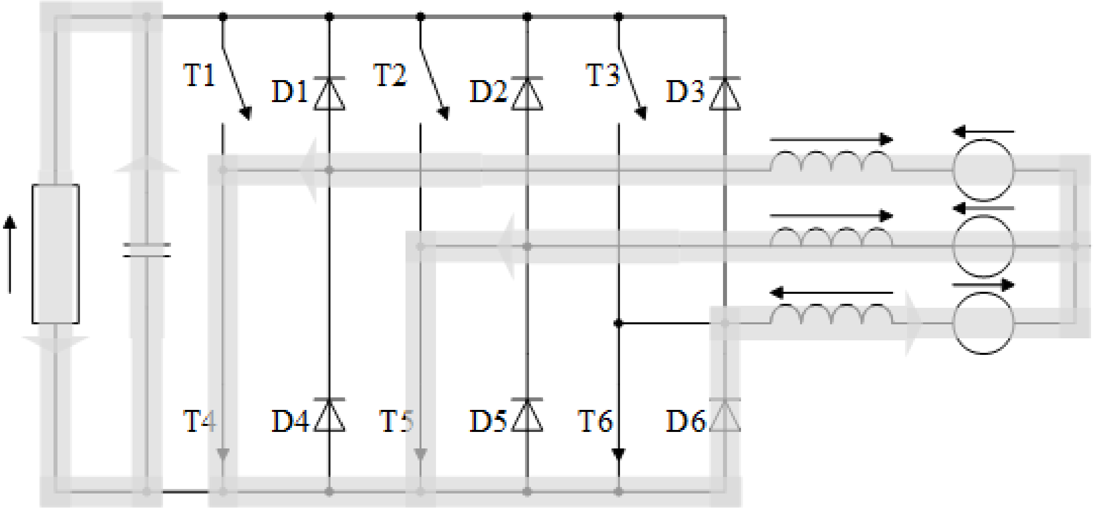
Figur 6.45: Vekselretterdrift ved tidspunkt t_4

En ser av figur 6.45 at DC- og AC-siden igjen er atskilt. DC-kilden lader opp kondensatoren. Siden det ikke er noen kilde som driver linjestrømmene, vil de avta.

Siden det er et visst spenningsfall over induktansene (se figur 6.43 og 6.44), må likespenningen være noe høyere enn toppverdien av vekselspenningen for at omformeren skal kunne gå som vekselretter.

Omformeren som likeretter
I fase L1 og L2 går det strømmer inn i omformeren, mens strømmen i L3 flyter ut av omformeren.

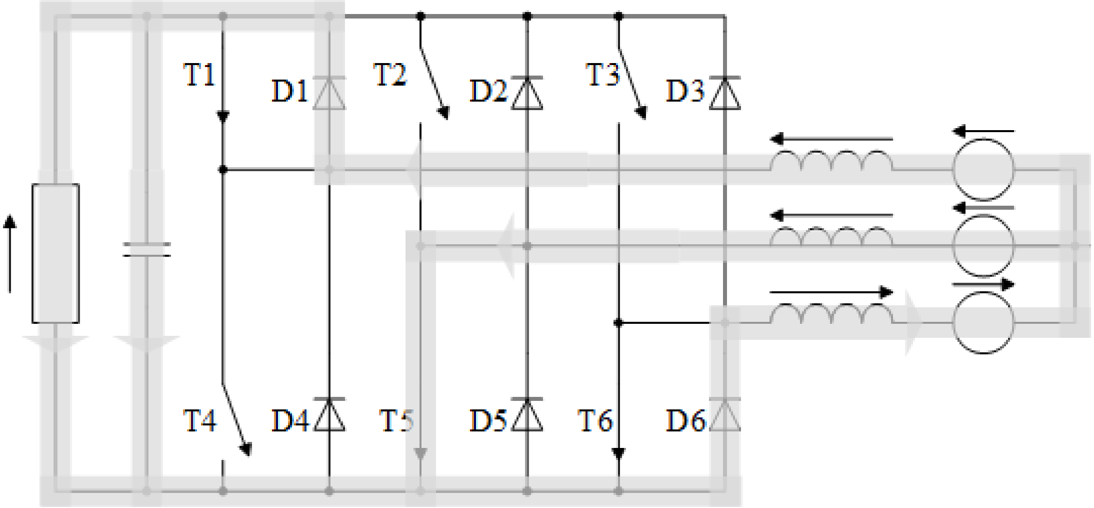
Tidspunkt t_1 (T4, T5 og T6 leder)



Figur 6.46: Likeretterdrift ved tidspunkt t_1

En ser av figur 6.46 at DC- og AC-siden er atskilt. Kondensatoren lader ut og forsyner DC-lasten. T4 og T5 leder, mens returstrømmen går gjennom friløpsdioden D6. Nettspenningene driver strømmene, og disse vil derfor tilta.

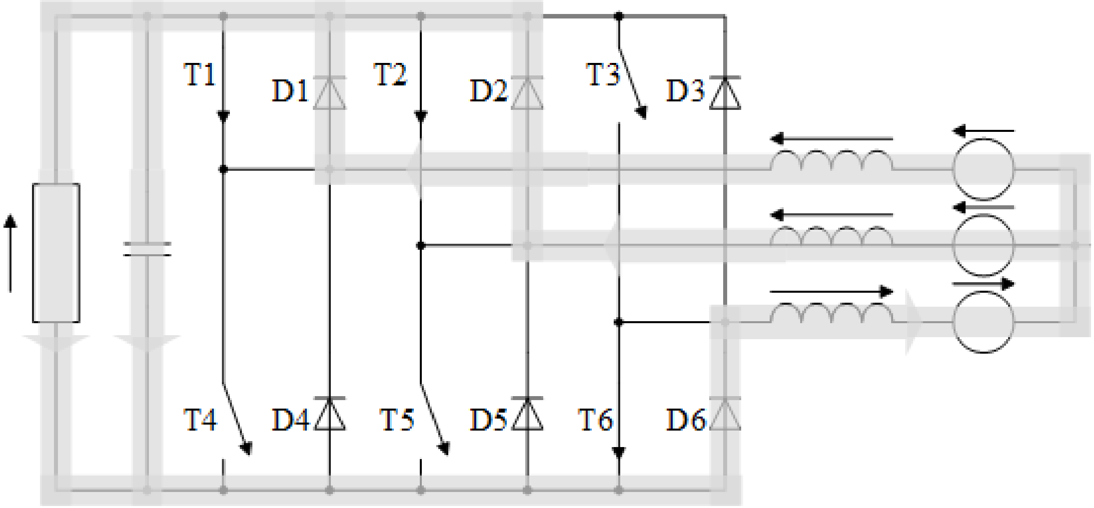
Tidspunkt t_2 (T1, T5 og T6 leder)



Figur 6.47: Likeretterdrift ved tidspunkt t_2

Som det fremgår av figur 6.47, danner D1 forbindelse mellom DC- og AC-siden. Både DC-lastenen og kondensatoren forsynes med strøm gjennom omformeren. DC-kretsen får AC-strømmene til å avta.

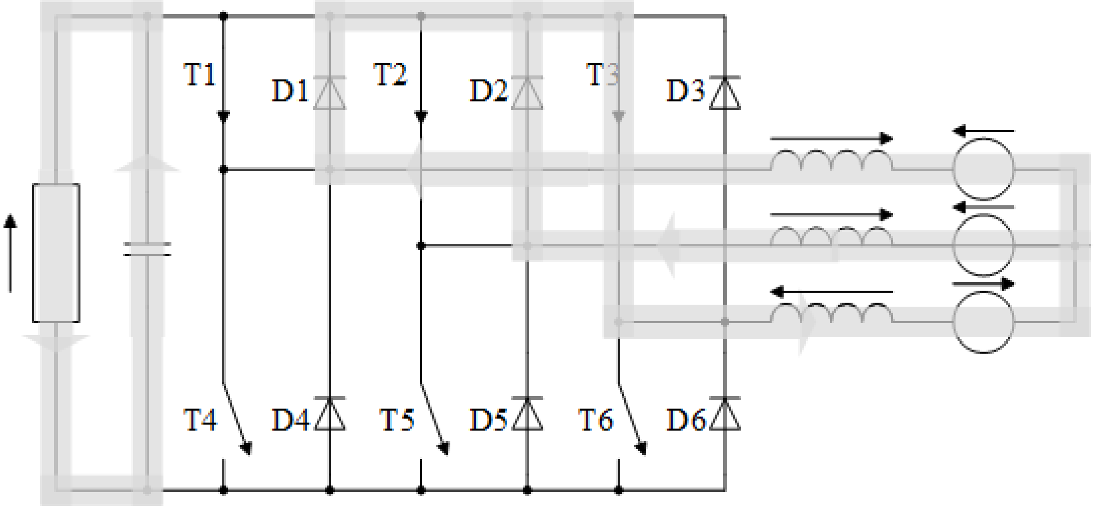
Tidspunkt t_3 (T1, T2 og T6 leder)



Figur 6.48: Likeretterdrift ved tidspunkt t_3

Figur 6.48 viser omtrent samme driftssituasjon som figur 6.47, bortsett fra at ingen transistorer er strømførende.

Tidspunkt t_4 (T1, T2 og T3 leder)



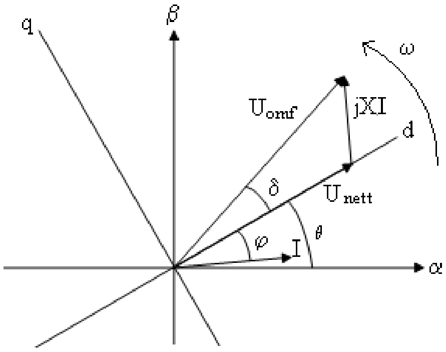
Figur 6.49: Likeretterdrift ved tidspunkt t_4

En ser av figur 6.45 at DC- og AC-siden igjen er atskilt. Kondensatoren forsyner DC-lasten. Siden det ikke er noen DC-last som hindrer linjestrømmene, vil de tilta.

Siden spenningsfallet over induktansene går i samme retning som nettspenningen (se figur 6.47 og 6.48), må likespenningen være noe høyere enn toppverdien av vekselspenningen. Hvis likespenningen ligger lavere enn vekselspenningens toppverdi, vil friløpsdiodene fungere som ei vanlig trefase diodebru, og transistorene vil ikke ha noen funksjon. Kretsen fungerer da som en likeretter, men uten styring.

6.10 Vektorstyring

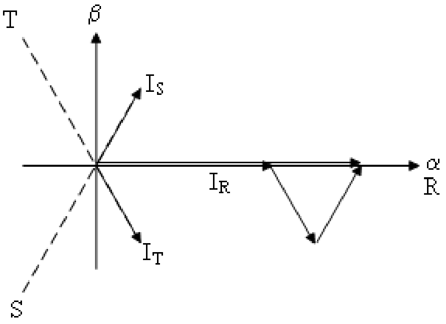
Som figur 6.38 viser, bestemmes effektflyten av omformerspenningenes amplituder og vinkler, referert til nettspenningen. En vanlig måte å styre trefaseomformeren på, er å benytte såkalt vektorstyring. Nettspenningene er da representert ved en roterende vektor, omformerspenningene ved en annen og linjestrømmene ved en tredje. Dette er illustrert på figur 6.50. Vektorene kan refereres til et stillestående koordinatsystem $\alpha - \beta$ eller et roterende system $d - q$. For det roterende systemet kan man velge ulike referanser, men det vanligste er å benytte nettspenningene som referanse.



Figur 6.50: Roterende strøm- og spenningsvektorer

Overgangen fra et trefasesystem til en roterende vektor består i å summere fasespenningene eller linjestrømmene vektorielt, som angitt i formel 6.41. Dette er illustrert på figur 6.51. I dette tilfellet har strømmen i fase R positivt maksimum, mens strømmene i fase S og T er negative, og halvparten så store. Stømvektoren vil da ligge langs α-aksen.

$$\begin{aligned} \overrightarrow{U} &= \tfrac{2}{3}\left(\overrightarrow{U}_{Rf} + \overrightarrow{U}_{Sf} + \overrightarrow{U}_{Tf}\right) \\ \overrightarrow{I} &= \tfrac{2}{3}\left(\overrightarrow{I}_{R} + \overrightarrow{I}_{S} + \overrightarrow{I}_{T}\right) \end{aligned} \tag{6.41}$$



Figur 6.51: Omforming fra trefasestrømmer til roterende strømvektor

Omformingen kalles Clarke-transformasjon og gjøres som vist i formel 6.42:

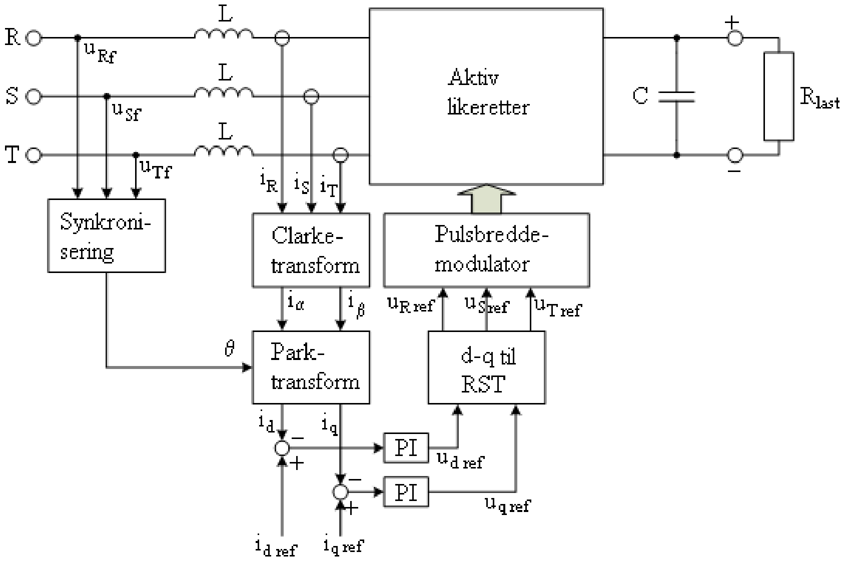
$$\begin{aligned} \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} &= \tfrac{2}{3}\begin{bmatrix} 1 & -0,5 & -0,5 \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} u_{Af} \\ u_{Bf} \\ u_{Cf} \end{bmatrix} \\ \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} &= \tfrac{2}{3}\begin{bmatrix} 1 & -0,5 & -0,5 \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} i_{A} \\ i_{B} \\ i_{C} \end{bmatrix} \end{aligned} \tag{6.42}$$

Regulatorer har ofte betydelige tidskonstanter, og det er derfor krevende å regulere størrelser som pulserer med $50\,\mathrm{Hz}$, slik som ovennevnte vektorer. Ved å benytte et roterende koordinatsystem, vil strømmer og spenninger fremstå som tilnærmet statiske og vil være mye enklere å styre. Denne overgangen fra stillestående til roterende koordinatsystem kalles Park-transformasjon og er definert i formel 6.43:

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix}$$
$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{6.43}$$

Referansevinkelen θ forteller hvordan det roterende systemet er orientert i forhold til det stasjonære til enhver tid. Dersom man velger nettspenningene som referanse, vil $\theta = 0$ når fasespenningen i fase R har sitt positive maksimum (U_{Rf} peker langs positiv x-akse, α-aksen).

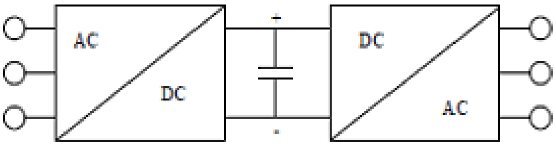
Figur 6.52 viser systemet anvendt på en aktiv likeretter. Aktiv og reaktiv effektflyt styres av de to referanseverdiene på inngangene til strømregulatorene.



Figur 6.52: Aktiv likeretter med vektorstyrte strømregulatorer

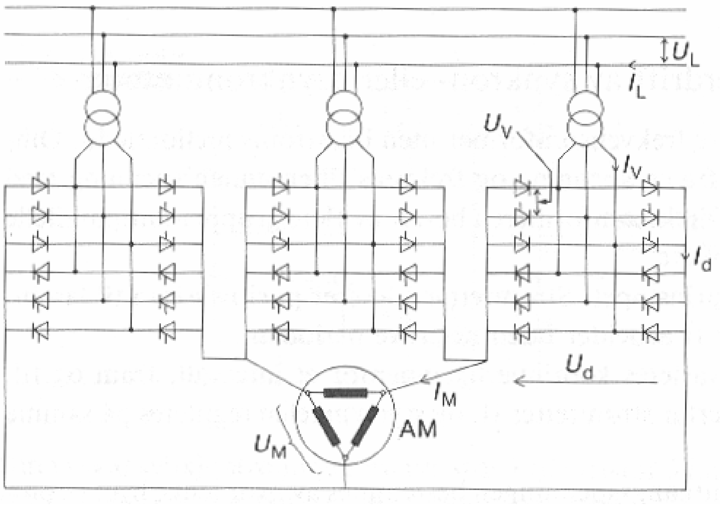
6.11 Frekvensomformere

Vanligvis når det er behov for å omforme vekselstrøm fra en frekvens til en annen, eller mellom enfase- og trefasesystemer, brukes to omformere med DC mellomkrets, som vist på figur 6.53. Til venstre i figuren er en likeretter, og til høyre er en vekselretter, og disse er koblet sammen ved hjelp av en likestrømskrets.



Figur 6.53: Strømrettere med DC mellomkrets

Denne koblingen brukes i frekvensstyring av motorer, og den brukes også i en såkalt vekselretterkaskade på asynkronmaskiner med sleperinger. Koblingen brukes også på vindturbiner hvor generatoren har en annen frekvens enn nettet, det vil si turbiner med såkalt pitchkontroll (vridbare rotorblad). En type AC-AC omformere som ikke benytter mellomkrets, er cyclokonverteren. Den kan omforme en vekselspenning til en annen vekselspenning av lavere frekvens og brukes først og fremst på langsomtgående motordrifter med stor effekt. Kretsen er vist på figur 6.54.

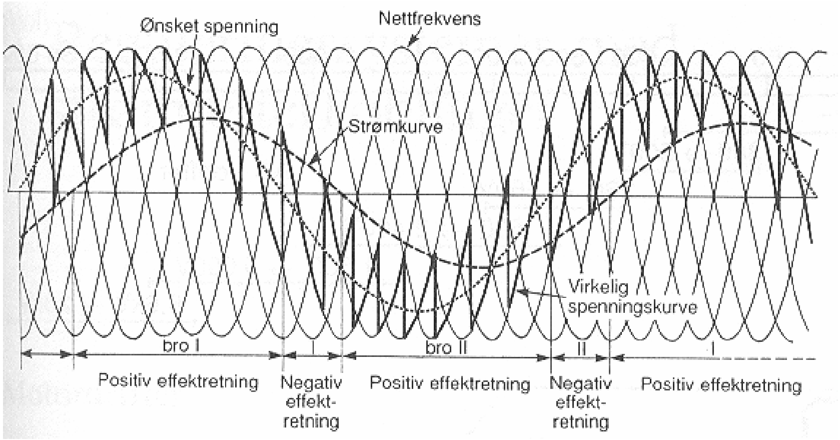


Figur 6.54: Trefase motordrift med cyclokonverter

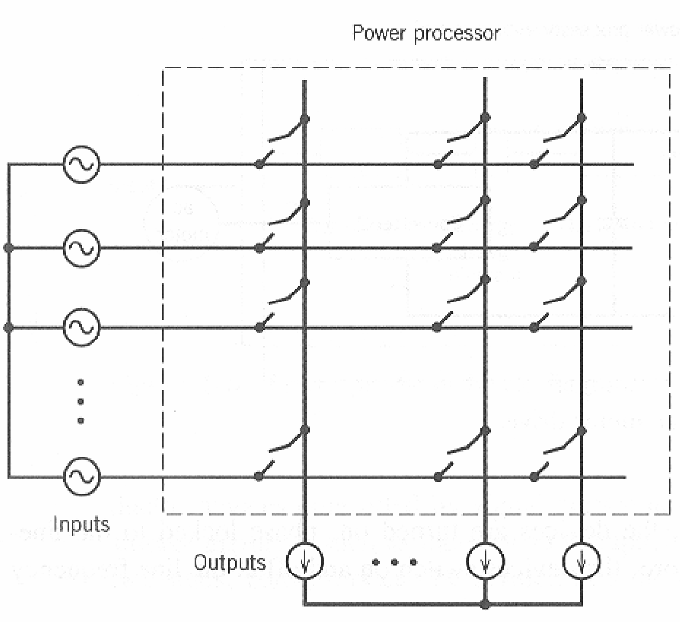
Som det fremgår av figuren, inneholder hver motorfase to trefase tyristorbroer i antiparallell. Dermed kan man styre både amplitude og polaritet på den midlere spenningen i hver motorfase. På grunn av at øyeblikksverdiene av fasespenningene i de tre omformerne er forskjellig, er det behov for galvanisk skille mellom kretsene. Derfor er hver faseomformer tilkoblet nettet over en egen transformator. Alternativet er å bruke galvanisk skilte motorviklinger.

Figur 6.55 viser spenningskurvene for en av motorfasene. Til venstre i figuren er den ene broa aktiv og genererer en tiltagende positiv spenning, for så å avta igjen. Etter at styrevinkelen er ført til $\alpha = 90°$, overtar den andre broa og fullfører resten av den lavfrekvente nettperioden.

En annen type direkte AC-AC omformere er matriseomformeren, som er vist på figur 6.56. Som navnet tilsier, består den av en matrise av svitsjer som kobler sammen to elektriske kretser. Omformeren har ingen reaktive komponenter (spoler eller kondensatorer), og den kan koble sammen systemer med ulike faser og frekvenser (trefase-til-trefase, enfase-til-trefase, trefase-til-enfase, trefase-til-likestrøm, likestrøm-til-enfase osv.)



Figur 6.55: Spenningskurver for en av motorfasene



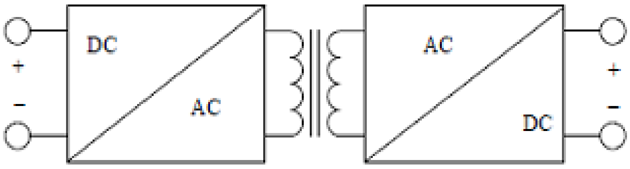
Figur 6.56: Matriseomformer på generell form

Matriseomformeren har likevel en del begrensninger som gjør at den ikke har fått det store gjennombruddet. For det første må det ene systemet være strømmatet og det andre spenningsmatet. Hvis ikke, vil omformeren belastes med store utjevningsstrømmer eller høye overspenninger. For det andre må det benyttes toveis svitsjer. Siden verken tyristorer eller transistorer leder i begge retninger, må to komponenter kobles i antiparallell for å løse oppgaven. For det tredje må inn- og utkoblingen skje svært presis. Hvis ikke, risikerer en å kortslutte spenningskilder eller å bryte strømkilder. For det fjerde ligger det begrensninger i hvor høy spenning en kan ta ut på den strømmatede siden eller hvor høy strøm en kan ta ut på den spenningsmatede siden.

Matriseomformeren er en tilsynelatende enkel design som per i dag viser seg å kreve mange halvlederkomponenter, samt reaktive komponenter (strøm- og spenningsmating). Det forskes likevel mye på denne omformerløsningen, og derfor er den tatt med i dette kompendiet.

6.12 Likestrømsomformere

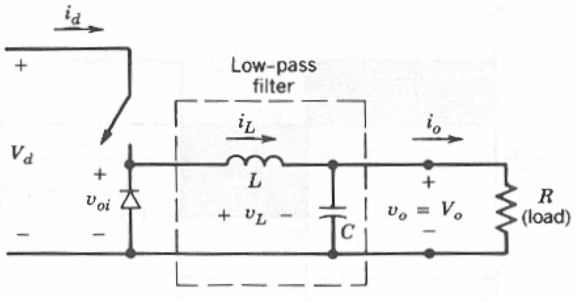
På samme måte som man kan bruke en DC mellomkrets for AC-AC omforming, kan man bruke en AC mellomkrets for DC-DC omforming. Dette er vist på figur 6.57. Vekselretteren forsyner en transformator som igjen forsyner en likeretter. Omsetningsforholdet bestemmes ved valg av transformator. Omformeren gir galvanisk skille mellom de to likestrømskretsene.



Figur 6.57: Likestrømsomformer med AC mellomkrets

Dersom det ikke er behov for galvanisk skille mellom kretsene, vil en direkte likestrømsomformer (en chopper) være enklere å bruke. Den baserer seg på pulsede spenninger og kan derfor ikke benytte tyristorer som svitsjer. De tre mest vanlige typene er nedtransformerende (buck) omformer, opptransformerende (boost) omformer og opp-ned-transformerende (buck-boost) omformer.

Nedtransformerende omformer
Vi skal først se på den nedtransformerende omformeren. Den er vist på figur 6.58.



Figur 6.58: Nedtransformerende likestrømsomformer

Svitsjen som på figuren er illustrert med en pil, vil vanligvis være en MOSFET eller IGBT transistor. Under svitsjen står en friløpsdiode. Resten av kretsen består av en induktans og kapasitans som til sammen utgjør et lavpassfilter som reduserer strøm- og spenningsrippel i kretsen.

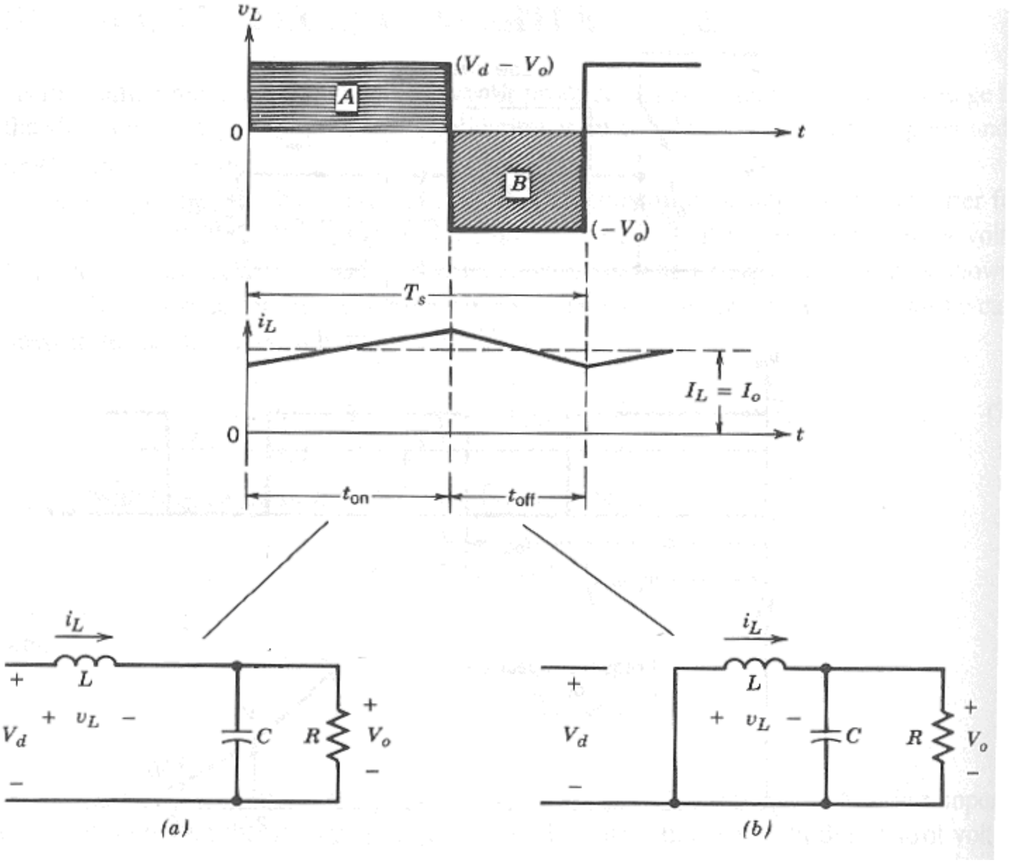
Figur 6.59 viser spennings- og strømkurvene for kretsen. Øverste diagram viser spenningen over spolen. Det neste viser strømmen gjennom spolen. I den tiden svitsjen er på, vil kilden U_d være koblet i serie med spolen og parallellkoblingen mellom kondensatoren og lastresistansen. Det skjer en økning i magnetfeltet proporsjonalt med det skraverte arealet A. Spolespenningen utgjør differansen mellom kildespenningen U_d og utgangsspenningen U_o. Når svitsjen er åpen, vil spolespenningen være lik utgangsspenningen U_o. Magnetfeltet reduseres proporsjonalt med det skraverte arealet B.

Ved å øke pulsforholdet, økes utgangsspenningen, men den kan aldri bli høyere enn inngangsspenningen. Utgangsspenningen er gitt ved formel (6.44), forutsatt kontinuerlig strøm:

$$U_o = \frac{t_{on}}{T_{sw}} U_d = d \cdot U_d \tag{6.44}$$

For strømmen i kretsen vil forholdet være omvendt:

$$I_o = \frac{1}{d} I_d \tag{6.45}$$



Figur 6.59: Strømmer og spenninger i nedtransformerende likestrømsomformer

Eksempel 12 *En bil er utstyrt med 24V startbatteri. Det er behov for 12V strømforsyning til en del ekstrautstyr, blant annet en bilstereo. Dette ekstrautstyret har i et driftstilfelle en samlet laststrøm på 5,0A. En nedtransformerende chopper benyttes for å forsyne utstyret. Regn ut pulsforholdet, samt tilført strøm fra batteriet, når en ser bort fra svitsjetap.*

Løsning:
Inngangsspenningen $U_d = 24\,\mathrm{V}$, og utgangsspenningen $U_0 = 12\,\mathrm{V}$. Pulsforholdet blir da

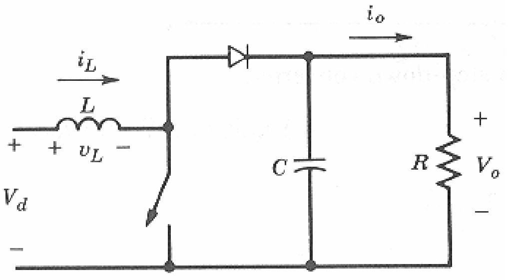
$$d = \frac{U_0}{U_d} = \frac{12}{24} = 0,5$$

Tilført strøm er

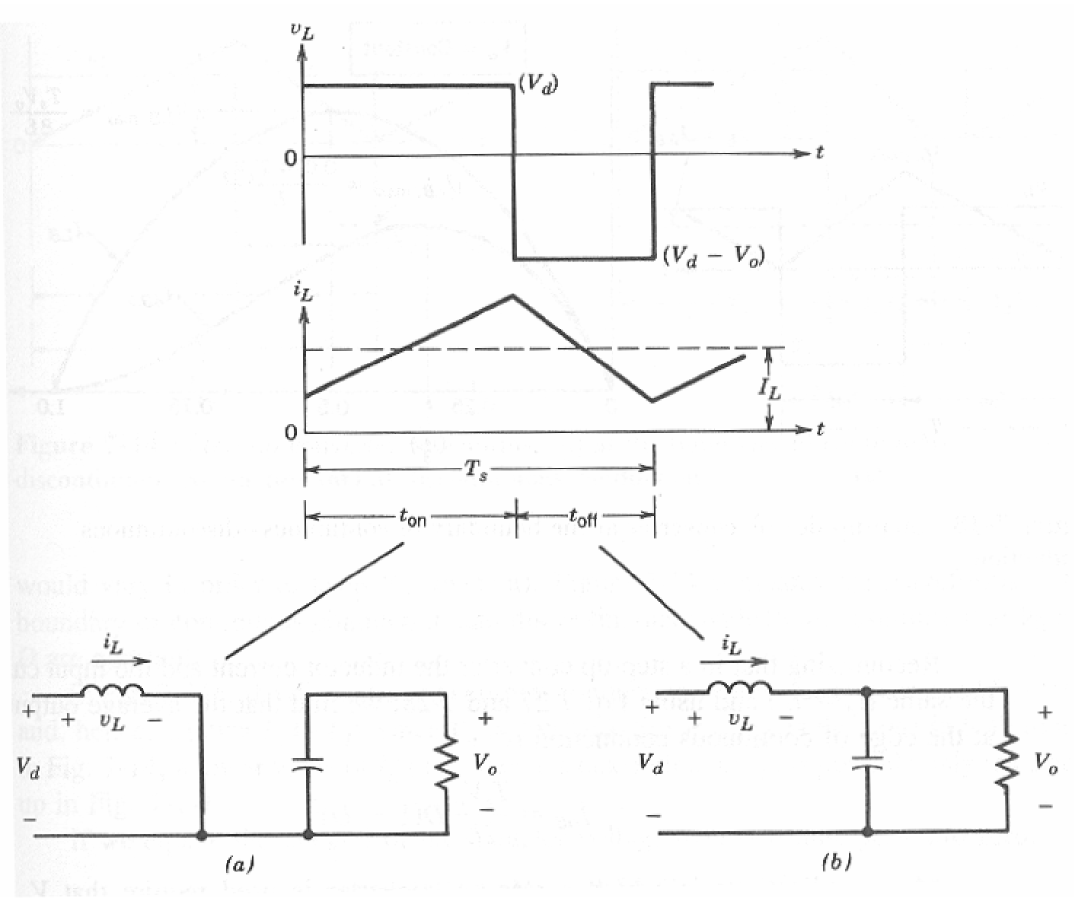
$$I_d = I_o \cdot d = 5,0 \cdot 0,5 = 2,5\,\mathrm{A}$$

Opptransformerende omformer

En nedtransformerende DC-DC omformer vil være anvendelig dersom man for eksempel har bruk for å ta ut en svakstrøms DC-spenning fra et lavspent DC-nett. Omvendt kan det være aktuelt å transformere opp en DC-spenning når man ønsker å koble solcellepaneler til nettet. DC-kretsen i en aktiv vekselretter som er nettilkoblet har vanligvis en spenning på flere hundre volt. For å slippe å seriekoble svært mange solcellepaneler, kan man i stedet bruke en opptransformerende DC-DC omformer. Den prinsipielle oppbygningen er vist på figur 6.60, og strømmer og spenninger er vist på figur 6.61.



Figur 6.60: Opptransformerende DC-DC omformer



Figur 6.61: Strømmer og spenninger i opptransformerende DC-DC omformer

Kretsen inneholder samme elementer som den nedtransformerende omformeren, men de er arrangert litt annerledes. Når svitsjen er på, bygges det opp en strøm i induktansen som er koblet direkte til spenningskilden. Samtidig lades kondensatoren ut gjennom lastresistansen. Når svitsjen ligger åpen, vil kildespenningen og spolespenningen ligge i serie med hverandre. Kondensatoren blir derfor ladet opp med en spenning som er høyere enn kildespenningen, og kretsen vil dermed være opptransformerende. Spenningsomsetningen er gitt ved

$$U_o = \frac{1}{1-d} U_d \tag{6.46}$$

og strømomsetningen blir

$$I_o = (1-d)\, I_d \tag{6.47}$$

Eksempel 13 *En solcellevegg bestående av flere serie- og parallellkoblede solcellepaneler avgir en varierende spenning. I ett driftstilfelle leverer anlegget 120V og 50A. I et annet tilfelle er spenningen 160V og strømmen 35A. Anlegget skal tilkobles en likestrømskrets med en konstant spenning på 400V. Beregn pulsforholdet og utgangsstrømmen i de to driftstilfellene. Se bort fra svitsjetap.*

Løsning:
I tilfelle 1 er pulsforholdet

$$d = 1 - \frac{U_d}{U_o} = 1 - \frac{120}{400} = 0,7$$

Utgangsstrømmen er

$$I_o = (1-d)\, I_d = (1-0,7)\, 50 = 15\,\mathrm{A}$$

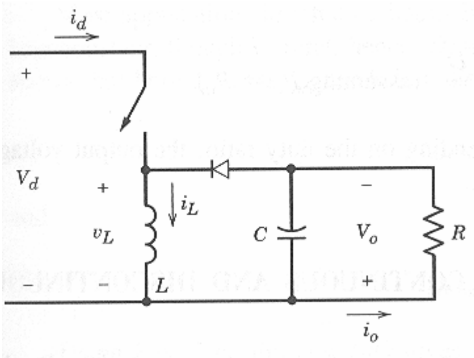
I tilfelle 2 er pulsforholdet

$$d = 1 - \frac{160}{400} = 0,6$$

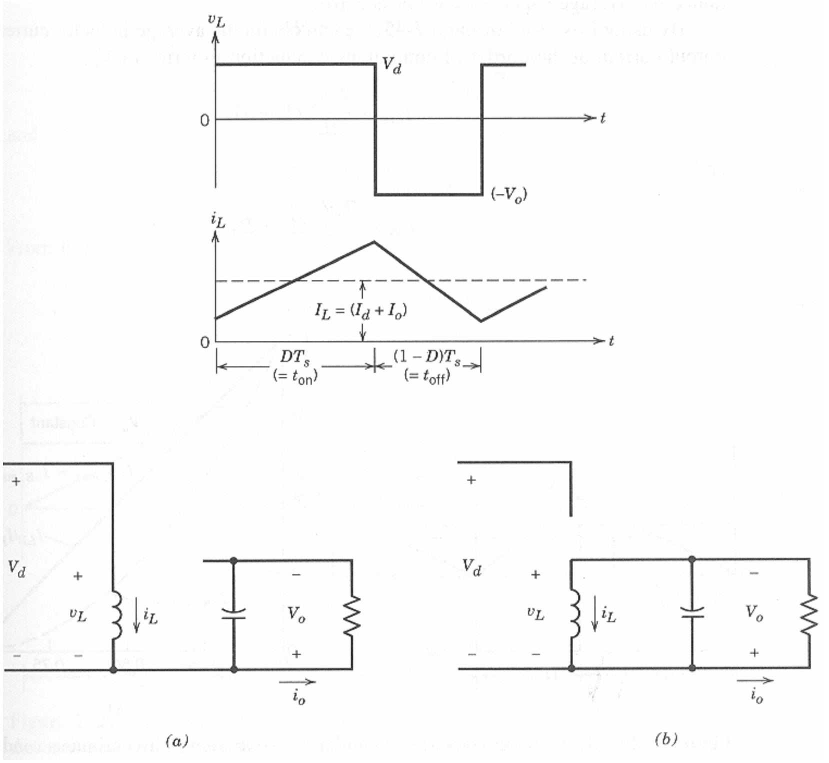
Utgangsstrømmen er

$$I_o = (1-0,6)\, 35 = 14\,\mathrm{A}$$

Opp-ned-transformerende omformer
Den tredje typen DC-DC omformere er den opp-ned-transformerende omformeren som er vist på figur 6.62 og 6.63.



Figur 6.62: Opp-ned-transformerende DC-DC omformer



Figur 6.63: Strømmer og spenninger i opp-ned-transformerende DC-DC omformer

Denne kretsen består av samme elementer som de to foregående, men er arrangert på en tredje måte. Den har mange likhetstrekk med den opptransformerende omformeren, men siden spolen ikke blir liggende i serie med kilden i den tiden svitsjen er utkoblet, gis det mulighet for at utgangsspenningen også kan ligge lavere enn kildespenningen. Dette er en omformer som egner seg dersom man har behov for å regulere DC-spenningen over et stort område. Spennings- og strømomsetningen er gitt ved henholdsvis formel (6.48) og (6.49):

$$U_o = \frac{d}{1-d} U_d \tag{6.48}$$

$$I_o = \frac{1-d}{d} I_d \tag{6.49}$$

Eksempel 14 *En 50V spenningskilde er tilkoblet en opp-ned-transformerende omformer som igjen forsyner en likestrømsmotor med en klemmespenning som varierer mellom 0 og 75V. Ved 75V trekker motoren en merkestrøm på 2,0A. Hva er pulsforholdet ved en motorspenning på 10V, på 50V og på 75V? Hvilken strøm leverer kilden ved en motorspenning på 75V? Se bort fra svitsjetap.*

Løsning:
Løser en formel 6.48 med hensyn på pulsforholdet, får en at

$$d = \frac{U_o}{U_d + U_o}$$

Ved $10\,\mathrm{V}$ klemmespenning blir pulsforholdet

$$d = \frac{10}{50 + 10} = 0,167$$

Ved $50\,\mathrm{V}$ klemmespenning får vi

$$d = \frac{50}{50 + 50} = 0,5$$

Ved $75\,\mathrm{V}$ klemmespenning blir pulsforholdet

$$d = \frac{75}{50 + 75} = 0,6$$

Kildestrømmen blir

$$I_d = \frac{d}{1 - d} I_o = \frac{0,6}{1 - 0,6} \cdot 2,0 = 3,0\,\mathrm{A}$$

Toveis DC-DC omformere (halvbru og fullbru)
De omformerne som er nevnt ovenfor, er ikke i stand til å overføre effekt i begge retninger og kan derfor ikke benyttes til for eksempel ladekontroll av en batteribank. Det fins en rekke DC-DC omformere som egner seg for toveis effektflyt, men de enkleste og vanligste er halvbru og fullbru. Figur 4.9 inneholder ei halvbru, som består av to transistorer med friløpsdioder. Figur 6.20 viser ei fullbru, som er satt sammen av to halvbruer. Tidligere i kompendiet har disse bruene blitt benyttet som vekselrettere, med varierende pulsbreddeforhold. Dersom pulsbreddeforholdet holdes konstant, vil både inngangs- og utgangsspenningen være likespenninger. På grunn av friløpsdiodene, vil både halvbruer og fullbruer være i stand til å overføre effekt i begge retninger.

7 Strøm- og spenningskvalitet

Som det fremgår av ordet, handler spenningskvalitet om hvor stabil og god nettspenningen er. Det er flere ulike forstyrrelser som kan redusere spenningskvaliteten. De viktigste er:

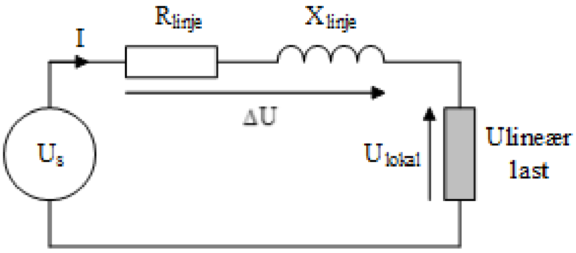
- Over- eller underspenninger. Skyldes ofte bortfall av last, produksjon eller overføringskapasitet, men kan også skyldes andre forhold.
- Usymmetriske spenninger. Kan skyldes skjev last, kortslutninger, jordslutninger eller fasebrudd.
- Flimmer. Hurtige spenningsendringer gir en opplevelse av at lyset blinker.
- Frekvensdrift. Skyldes alvorlige feil i nettet, ofte på grunn av at en del av nettet er atskilt fra resten av samkjøringsnettet (øydrift).
- Overharmarmoniske spenninger. Kan skyldes kraftelektronikk, lysrør og annen ulieær last, men kan også skyldes resonans, inn- og utkoblinger m. m.

Ulineær last
Vanlig last har en konstant impedans. Da vil linjestrømmene være sinusformede dersom påtrykte spenninger er sinusformede:

$$I_m \sin(\omega t) = \frac{U_m \sin(\omega t)}{R_{last} + jX_{last}}$$

I noen tilfelle endrer lastimpedansen seg med påtrykt spenning, for eksempel ei trafokjerne som går i metning når påtrykt spenning overskrider en viss verdi. Da vil linjestrømmene få en kurveform som avviker fra en ren sinus. Strømmene blir da en miks av den grunnharmoniske ($50\,\mathrm{Hz}$) og en eller flere overharmoniske strømkomponenter.

Spenningsfall i tilførselsledninger



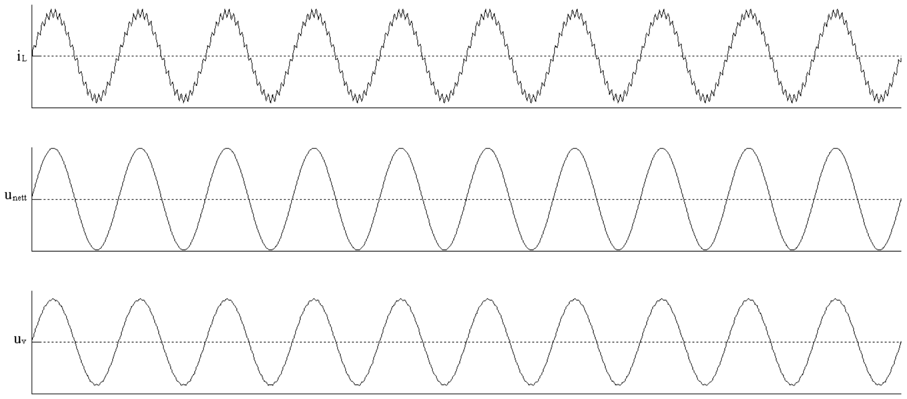
Figur 7.1: Seriekrets med linjeimpedans og ulieær last.

Dersom linjestrømmen I avviker fra sinusform, vil også spenningsfallet ΔU i tilførselsledningene avvike fra sinusform:

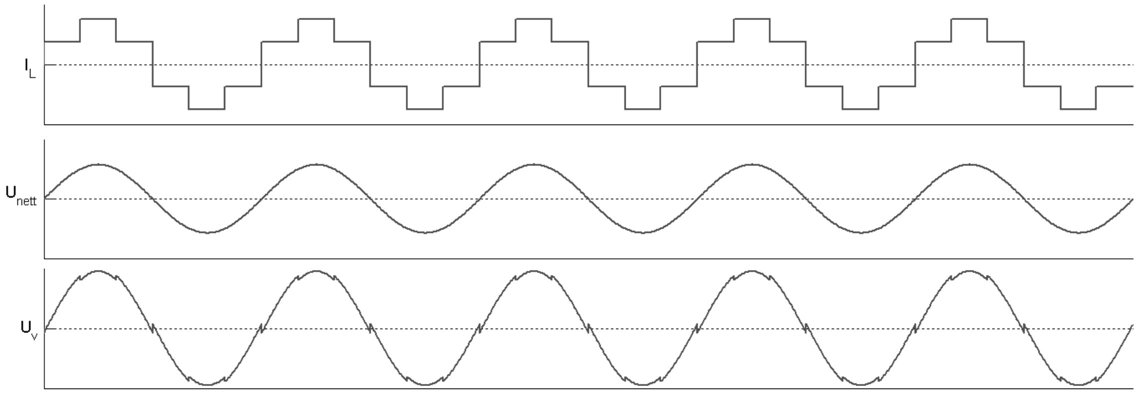
$$\Delta U(t) = (R + jX) I(t)$$

Spenningsfallet ΔU vil være mer eller mindre faseforskjøvet i forhold til linjestrømmen I, men vil ha samme kurveform. Dermed vil den lokale spenningen U_{lokal} avvike noe fra sinusform, selv om inngangsspenningen U_s er en ren sinus. Utstyr som befinner seg i nærheten av likeretteren vil da bli forsynt med en spenning av lavere kvalitet enn spenningen lenger ute i nettet.

Figur 7.2 viser hvordan strømrippelet påvirker spenningen lokalt for en aktiv strømretter. Figur 7.3 viser tilsvarende forhold for en tyristorlikeretter. En måte å bøte på dette, er å sette et filter foran omformeren. En annen løsning er å oppgradere tilførselsledningene, slik at linjeimpedansene reduseres.

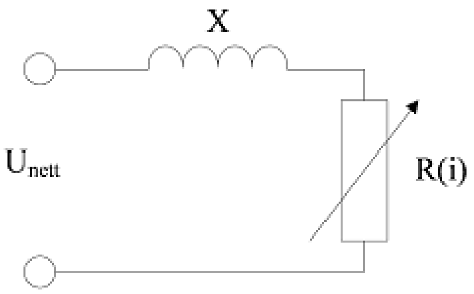


Figur 7.2: Strøm- og spenningsrippel for aktiv likeretter

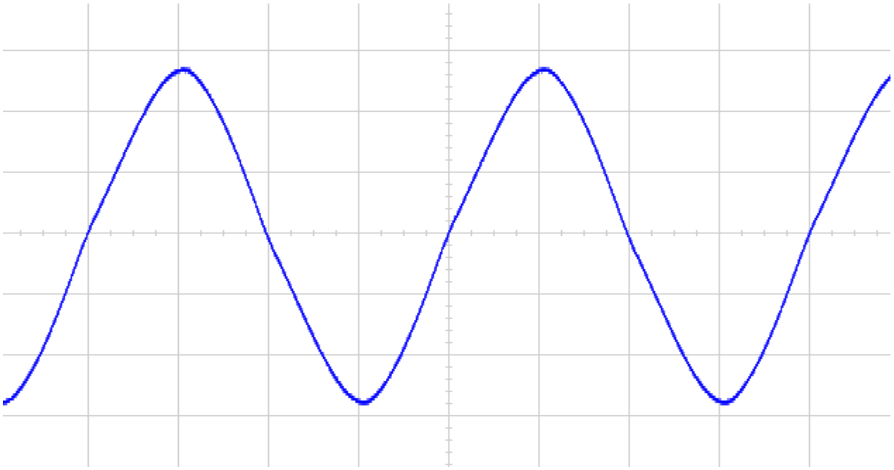


Figur 7.3: Strøm- og spenningsrippel for tyristorlikeretter

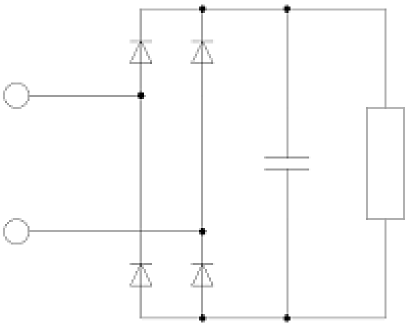
Ulike typer ulineær last
Direktekoblede lysrør må kobles i serie med en reaktans, også kalt en reaktorspole. Dette skyldes at selve lysrøret har en svært lav impedans, vist på figur 7.4 som en variabel resistans. Denne resistansen varierer med strømgjennomgangen. Ved lav strøm er resistansen høy, og den avtar med økende strøm. Derfor vil linjestrømmen avvike fra påtrykt spenning. Den vil bli mer triangelformet, og siden kretsen er mer reaktiv ved maksimum enn ved nullgjennomgang, vil toppene forskyves litt mot høyre. Dette fremkommer på figur 7.5.
Diodelikerettere med glattekondensator vil trekke korte ladepulser hver gang kondensatoren lades opp ved nettspenningens maksimum, som vist på figur 7.7. Figur 7.6 viser koblingsskjema for kretsen.



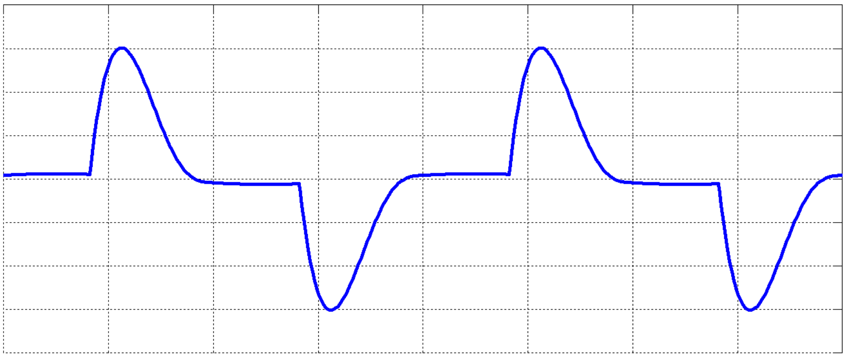
Figur 7.4: Forenklet ekvivalentkrets for direktekoblet lysrør



Figur 7.5: Linjestrøm i direktekoblet lysrørarmatur.

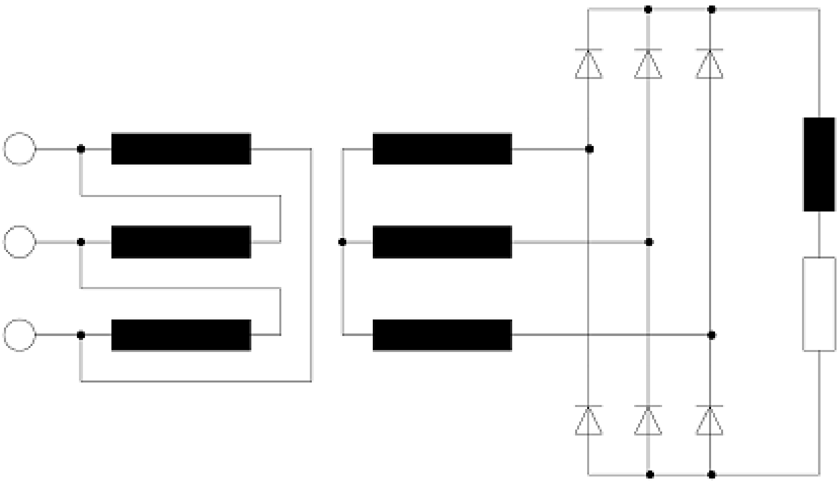


Figur 7.6: Toveis topuls enfasebru med C-filter

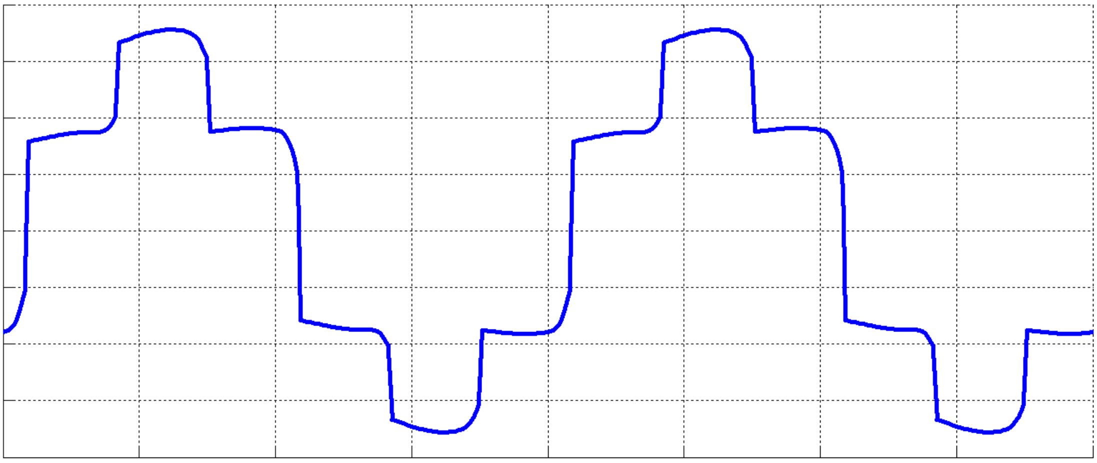


Figur 7.7: Linjestrøm for toveis topuls enfasebru med C-filter

Figur 7.8 viser en toveis sekspuls likeretter med strømglatting bak en Dy-koblet trafo. Linjestrømmenes kurveform er vist på figur 7.9.

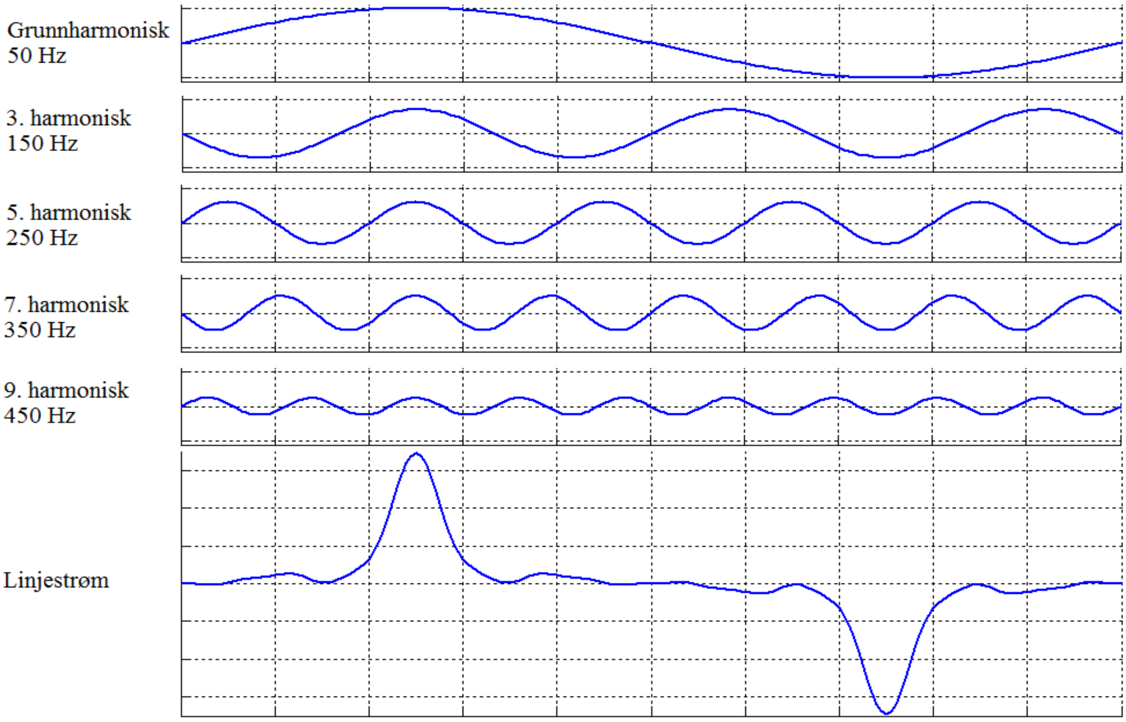


Figur 7.8: Toveis sekspuls trefasebru med strømglatting

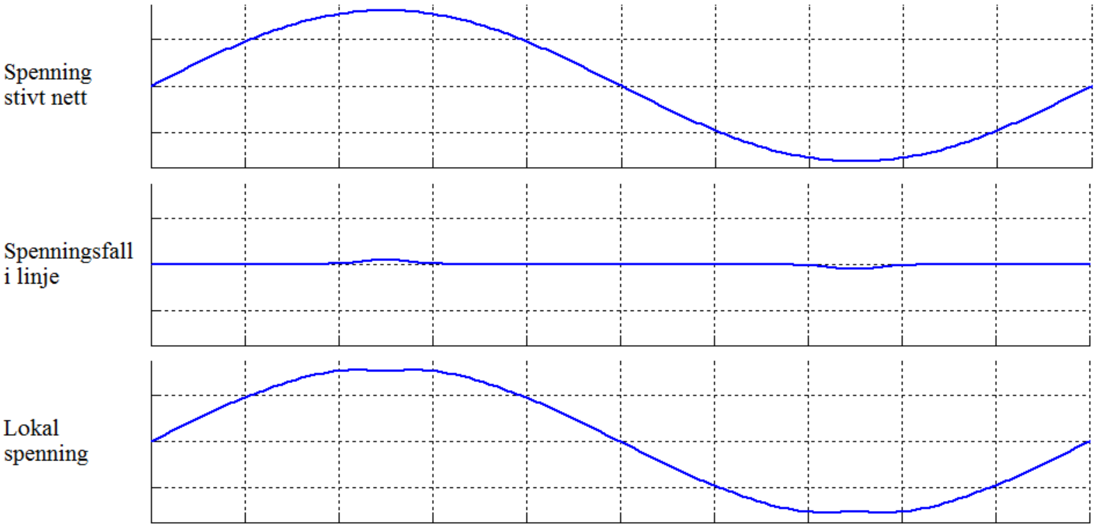


Figur 7.9: Linjestrøm for toveis sekspuls trefasebru

Overharmoniske strømmer
Ved å sette sammen ulike harmoniske strømkomponenter, kan man gjenskape den opprinnelige kurveformen, dersom signalet er periodisk. Figur 7.10 viser hvordan en blanding av ulike odde harmoniske strømkomponenter danner en pulset strøm som minner om strømkurven i figur 7.7. De korte strømpulsene gjør at spenningen blir flat på toppen i nærheten av likeretterlasten. Jo svakere nett, jo større spenningsfall, og jo mer forvrengt spenning lokalt.

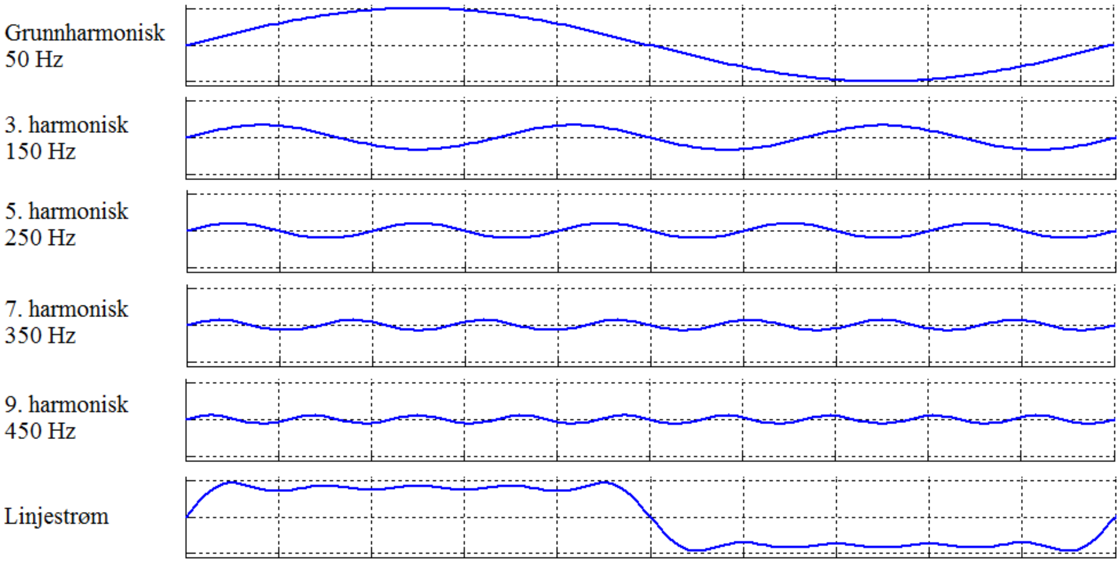


Figur 7.10: Pulset linjestrøm

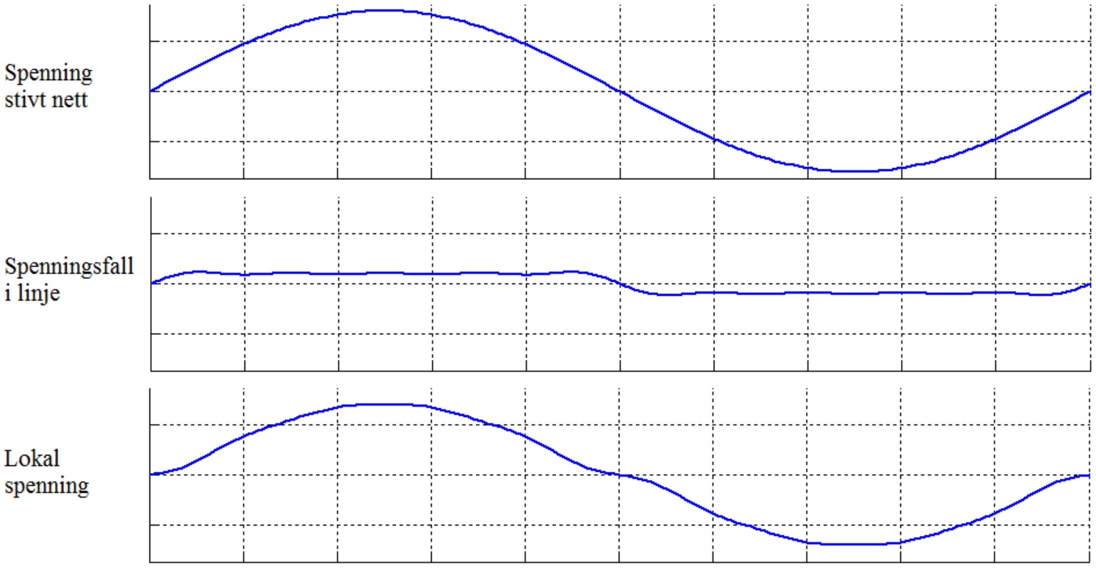


Figur 7.11: Spenningsfall for pulset linjestrøm

Dersom en diode- eller tyristorlikeretter har en strømmatet DC-krets, vil linjestrømmene bli nokså firkantede, slik det fremgår av figur 7.9. Figur 7.12 viser en syntese av overharmoniske som gir en strøm tilnærmet lik linjestrømmen inn i en enfaselikeretter med strømglatting. Spenningsfall og lokal spenning er vist på figur 7.13.

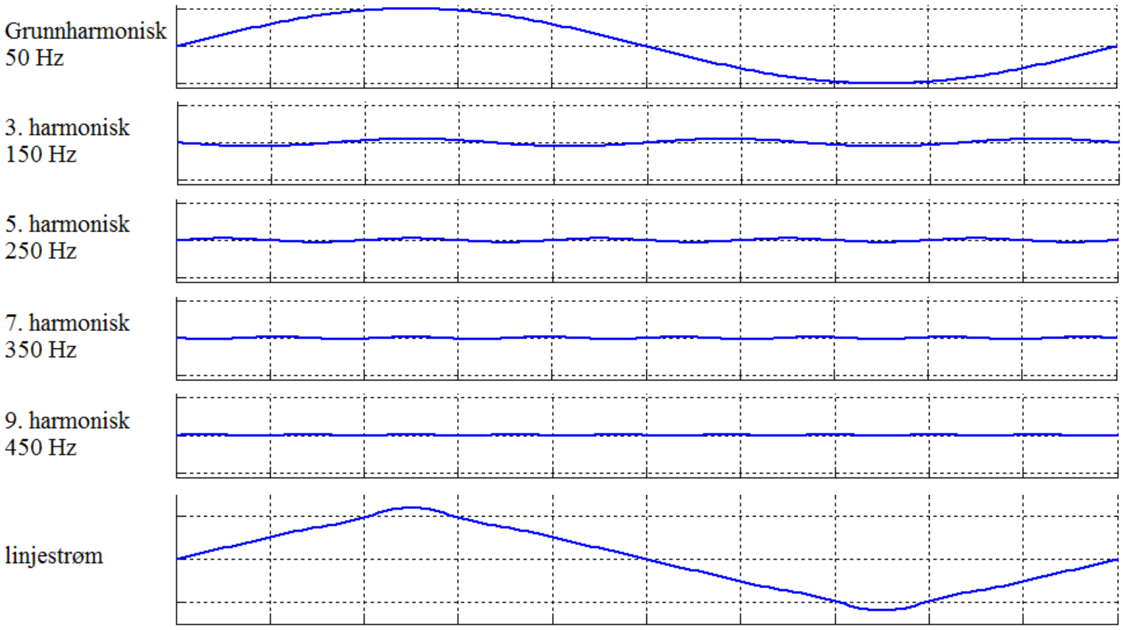


Figur 7.12: Firkantet linjestrøm

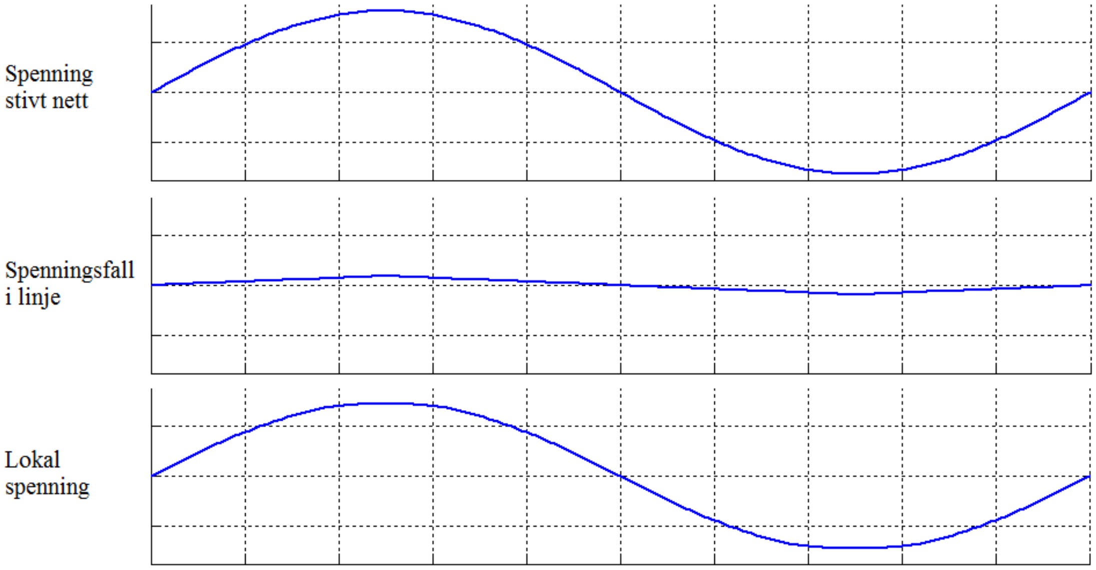


Figur 7.13: Spenningsfall ved firkantet linjestrøm

Som det fremgår av figur 7.5, vil et direktekoblet lysrør ha en nokså triangelformet linjestrøm. Dette er forsøkt gjenskapt på figur 7.14, med tilsvarende spenningsfall på figur 7.15. Den lokale spenningen blir noe flatere, men ikke mye forvrengt.

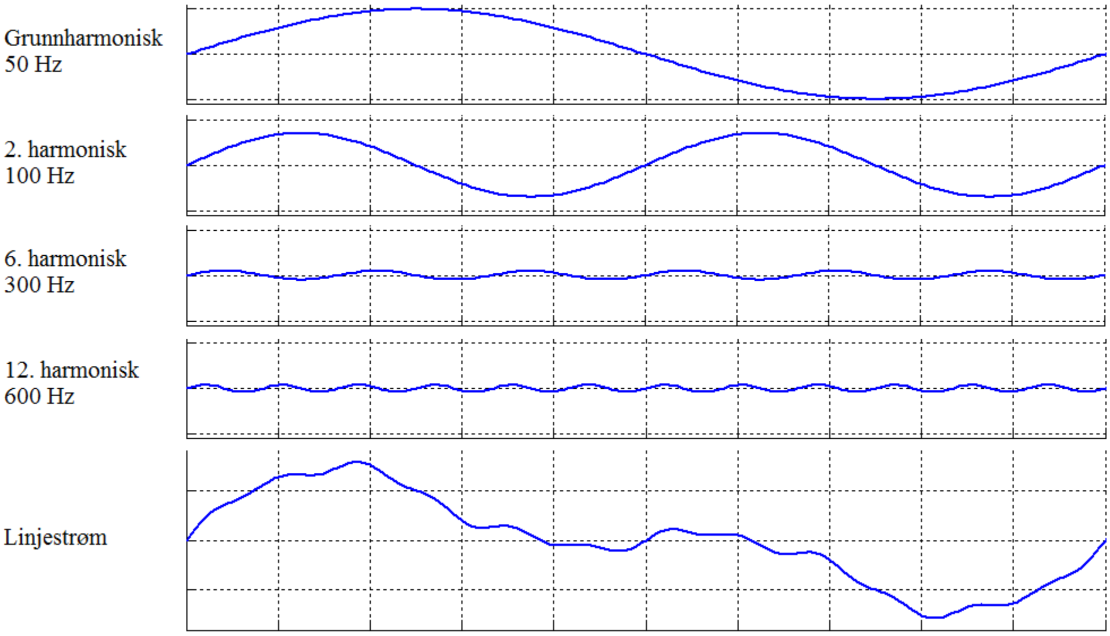


Figur 7.14: Triangelformet linjestrøm

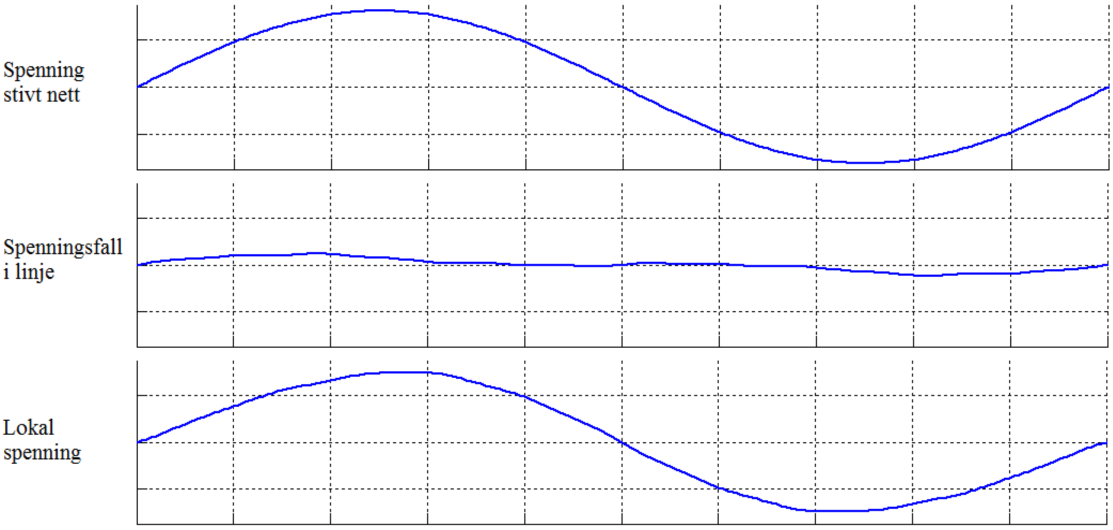


Figur 7.15: Spenningsfall ved triangelformet linjestrøm

I noen tilfelle er linjestrømmene punktsymmetriske og ikke aksesymmetriske, for eksempel ved enveis trepulskobling med strømglatting. Da vil strømmen inneholde likeharmoniske (2. harmonisk, 4. harmonisk osv). Syntesen på figur 7.16 illustrerer dette, og figur 7.17 viser at også lokale spenninger får en punktsymmerisk form på grunn av spenningsfallet i linjene.



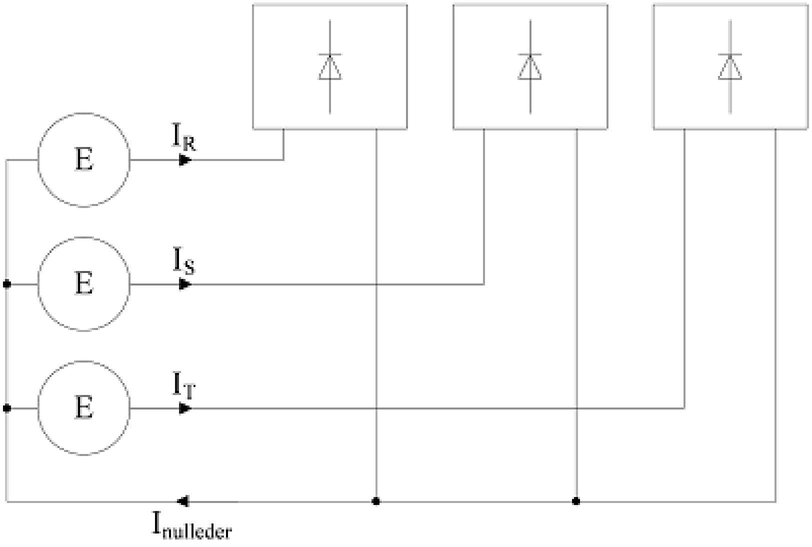
Figur 7.16: Linjestrøm med likeharmoniske strømkomponenter



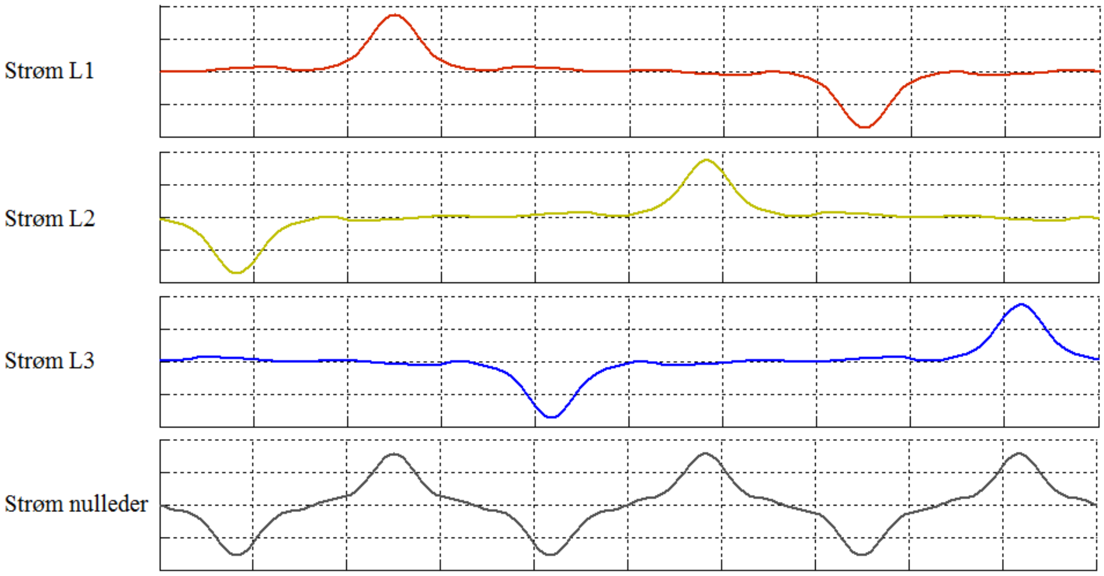
Figur 7.17: Spenningsfall for linjestrøm med likeharmoniske

Strøm i nulleder

Noen ganger kan det være store mengder diodelikerettere på en kurs. Det kan for eksempel være datamaskiner, radio eller TV, lysrør med elektronisk ballast eller lading av el-biler. I et fireledernettverk som vist på figur 7.18 kobles hver lurs mellom faseleder og nulleder. Nullederen er en felles returleder for alle fasene. Vanligvis vil fasestrømmene være sinusformede, og nullederstrømmen vil være tilnærmet lik null. Dersom linjestrømmene består av korte ladepulser med lange luker mellom, vil nullederstrømmen se ut omtrent som på figur 7.19. Når det går en ladepuls i en fase, er de andre fasene strømløse. Derfor vil alle ladepulsene hope seg opp i nullederen som dermed vil føre en mye høyere strøm enn faselederne. Det kan vises matematisk at dersom lasten utelukkende består av diodelikerettere med C-filter, vil nullederstrømmen være tilnærmet lik roten av tre ganger fasestrømmene.



Figur 7.18: Fireledernettverk med likeretterlast



Figur 7.19: Pulsede linjestrømmer og resulterende nullederstrøm

Eksempel 1 *Tre store diodelikerettere med C-filter er tilkoblet et TN-nett mellom faseledere og nulleder, som vist på figur 7.18. Strømpulsene er tilnærmet sinusformede, med en toppverdi på 45 A. Strømmene i faselederne og nulleder fordeler seg som vist på figur 7.19. Beregn effektivverdiene for fasestrømmene og nullederstømmen.*

Løsning:
Fasestrømmen i fase A er gitt ved

$$i_A(\omega t) = \begin{cases} 0 \text{ for } \omega t < \frac{\pi}{3} \\ -45\sin(3\omega t) \text{ for } \frac{\pi}{3} < \omega t < \frac{2\pi}{3} \\ 0 \text{ for } \frac{2\pi}{3} < \omega t < \frac{4\pi}{3} \\ -45\sin(3\omega t) \text{ for } \frac{4\pi}{3} < \omega t < \frac{5\pi}{3} \\ 0 \text{ for } \omega t > \frac{5\pi}{3} \end{cases}$$

Det er tilstrekkelig å beregne effektivverdien over en halvperiode:

$$I_A = \sqrt{\frac{1}{\pi}\int_0^{\pi} {i_A}^2(\omega t)\, d\omega t}$$

Integralet begrenser seg til et lite intervall:

$$\begin{aligned} \int_0^{\pi} {i_A}^2(\omega t)\, d\omega t &= \int_{\frac{\pi}{3}}^{\frac{2\pi}{3}} (-45\sin(3\omega t))^2 = 2025\int_{\frac{\pi}{3}}^{\frac{2\pi}{3}} \sin^2(3\omega t)\, d\omega t \\ \int_0^{\pi} {i_A}^2(\omega t)\, d\omega t &= \frac{2025}{3}\left[\frac{3\omega t}{2} - \frac{1}{4}\sin(6\omega t)\right]_{\frac{\pi}{3}}^{\frac{2\pi}{3}} = \frac{675\pi}{2} \end{aligned}$$

Effektivverdien blir da

$$I_A = \sqrt{\frac{1}{\pi}\frac{675\pi}{2}} = \sqrt{\frac{675}{2}} = 18,4\,\mathrm{A}$$

Effektivverdien av nullederstrømmen er

$$I_N = \frac{45}{\sqrt{2}} = 31,8\,\mathrm{A}$$

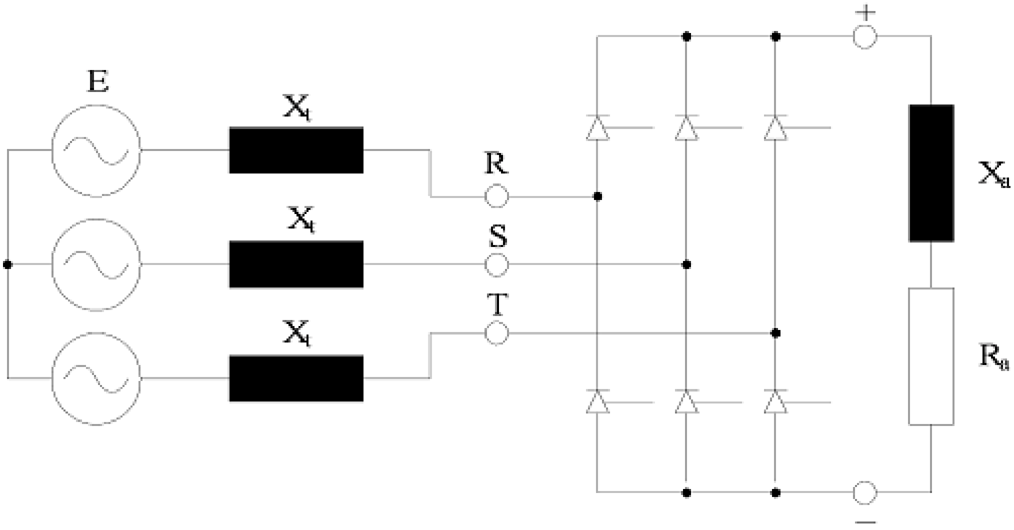
En ser altså at strømmen i nulleder er roten av 3 ganger større enn fasestrømmene.

7.1 Øvingsoppgaver

1. Hva er forskjellen på strøm- og spenningsmatede likestrømskretser?

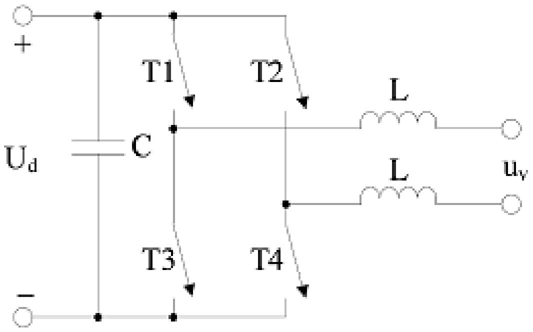
2. Det skal designes en diodelikeretter basert på toveis topulskobling med glattekondensator. Hver av diodene har et spenningsfall på $0,7\,\mathrm{V}$. Likeretteren kobles til et $230\,\mathrm{V}$ $50\,\mathrm{Hz}$ nett via en transformator. Liketteren skal kunne belastes med $0,5\,\mathrm{A}$ ved en spenning på $12\,\mathrm{V}$, og spenningsrippelet skal ikke overskride $1,0\%$ ved denne belastningen. Beregn transformatorens spenningsomsetning og effekt, samt størrelsen på glattekondensatoren.

3. Figur 7.20 viser ei fullstyrt bru med en likestrømsmotor modellert som en lekkreaktans X_a og en resistans R_a. Motorens lekkreaktans antas å være så stor at likestrømmen er glatt. Omformeren er tilkoblet et $230\,\mathrm{V}$ $50\,\mathrm{Hz}$ trefasenett. Transformatorens lekkreaktans X_t er $1,0\,\Omega$. I et driftstilfelle trekker motoren $10\,\mathrm{A}$ ved en klemmespenning på $150\,\mathrm{V}$. Hvilken styrevinkel må en da bruke?



Figur 7.20: Fullstyrt bru med likestrømsmotor

4. Figur 7.21 viser en enfase vekselretter med pulsbreddemodulering. Omformeren mates med $200\,\mathrm{V}$ likespenning. Beregn største og minste pulsforhold ved en vekselspenning på $50\,\mathrm{V}$. Hvor store må induktansene være for at strømrippelet ikke skal overskride $100\,\mathrm{mA}$ når svitsjefrekvensen er $10\,\mathrm{kHz}$?



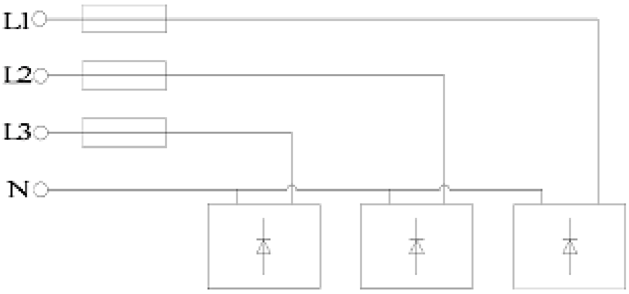
Figur 7.21: H-bru i vekselretterdrift

5. Hva hender hvis styrespenningen $U_{control}$ har høyere amplitude enn triangelspenningen U_{tri}? Hvilken kurveform får vekselspenningen hvis overmodulasjonen er svært kraftig?

6. På hvilken måte kan en likeretter med pulsbreddemodulering forstyrre utstyr i nærheten hvis rippelet på linjestrømmene blir uforholdsmessig høyt?

7. En likespenning på $100\,\mathrm{V}$ mates inn på en DC-DC-omformer. Det tas ut en spenning som varierer mellom 75 og $130\,\mathrm{V}$. Hvilken type omformer må benyttes? Hva blir pulsforholdet ved en utgangsspenning på $115\,\mathrm{V}$, og hvor stor strøm trekker omformeren dersom lasten har en effekt på $500\,\mathrm{W}$? Se bort fra tap i omformeren?

8. Figur 7.22 viser et fireledernettverk med tre datalaber, her modellert som diodelikerettere. Hver av linjene L1 - L3 fører en strøm på $8,5\,\mathrm{A}$. Hvor stor strøm går i nullederen?

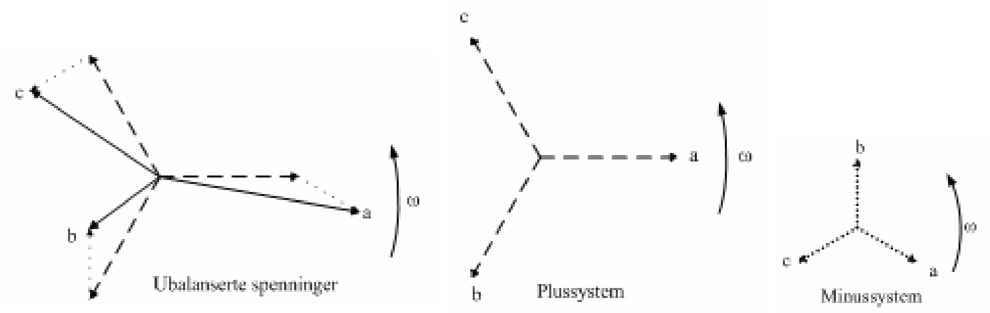


Figur 7.22: TN-nett med diodelikerettere

9. Hva er årsaken til at likeretterlasten på figur 7.22 forvrenger nettspenningen i nærliggende nett? På hvilken måte blir spenningskurven endret? Hvilke tiltak kan gjøres for å unngå dette?

8 Symmetriske komponenter

Dersom spenninger, strømmer og fluks i en trefasemaskin er usymmetriske, blir forholdene ganske fort komplekse og vanskelige å forstå. Da kan en benytte seg av det faktum at ethvert ubalansert trefasesystem kan modelleres som et balansert plussystem, et balansert minussystem, og noen ganger også et nullsystem. Figur 8.1 viser hvordan usymmetriske trefasespenninger eller -strømmer kan dekomponeres på denne måten.



Figur 8.1: Symmetriske spenningskomponenter

Plusskomponenten
Plusskomponenten av de ubalanserte størrelsene finnes ved å fasedreie og summere som vist i (8.1) og (8.2):

$$\begin{aligned}\overrightarrow{U}_{R+} &= \tfrac{1}{3}\left(\overrightarrow{U}_R + \overrightarrow{U}_S \cdot a + \overrightarrow{U}_T \cdot a^2\right)\\ \overrightarrow{I}_{R+} &= \tfrac{1}{3}\left(\overrightarrow{I}_R + \overrightarrow{I}_S \cdot a + \overrightarrow{I}_T \cdot a^2\right)\end{aligned} \tag{8.1}$$

$$\begin{aligned}\overrightarrow{U}_{S+} &= \overrightarrow{U}_{R+} \cdot a^2\\ \overrightarrow{U}_{T+} &= \overrightarrow{U}_{R+} \cdot a\\ \overrightarrow{I}_{S+} &= \overrightarrow{I}_{R+} \cdot a^2\\ \overrightarrow{I}_{T+} &= \overrightarrow{I}_{R+} \cdot a\end{aligned} \tag{8.2}$$

hvor $a = 1\angle 120\,^\circ = -\frac{1}{2} + j\frac{\sqrt{3}}{2}$ og $a^2 = 1\angle -120\,^\circ = -\frac{1}{2} - j\frac{\sqrt{3}}{2}$

Minuskomponenten
finnes ved (8.3) og (8.4):

$$\begin{aligned}\overrightarrow{U}_{R-} &= \tfrac{1}{3}\left(\overrightarrow{U}_R + \overrightarrow{U}_S \cdot a^2 + \overrightarrow{U}_T \cdot a\right)\\ \overrightarrow{I}_{R-} &= \tfrac{1}{3}\left(\overrightarrow{I}_R + \overrightarrow{I}_S \cdot a^2 + \overrightarrow{I}_T \cdot a\right)\end{aligned} \tag{8.3}$$

$$\begin{aligned}\overrightarrow{U}_{S-} &= \overrightarrow{U}_{R-} \cdot a\\ \overrightarrow{U}_{T-} &= \overrightarrow{U}_{R-} \cdot a^2\\ \overrightarrow{I}_{S-} &= \overrightarrow{I}_{R-} \cdot a\\ \overrightarrow{I}_{T-} &= \overrightarrow{I}_{R-} \cdot a^2\end{aligned} \tag{8.4}$$

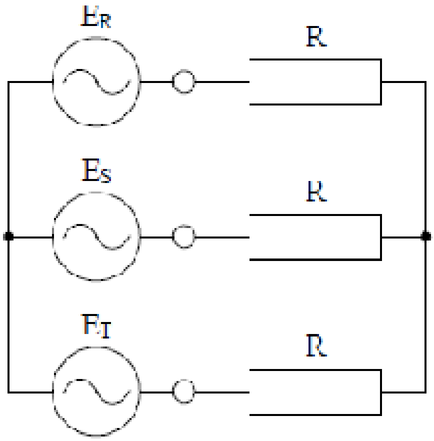
Nullkomponenten
er felles for alle tre faser og finnes ved (8.5):

$$\begin{aligned}\overrightarrow{U}_{R0} = \overrightarrow{U}_{S0} = \overrightarrow{U}_{T0} &= \tfrac{1}{3}\left(\overrightarrow{U}_R + \overrightarrow{U}_S + \overrightarrow{U}_T\right)\\ \overrightarrow{I}_{R0} = \overrightarrow{I}_{S0} = \overrightarrow{I}_{T0} &= \tfrac{1}{3}\left(\overrightarrow{I}_R + \overrightarrow{I}_S + \overrightarrow{I}_T\right)\end{aligned} \tag{8.5}$$

Eksempel 1 *Figur 8.2 viser et nettverk med ubalanserte spenninger og symmetrisk last. Data for nettverket er oppgitt i tabell 8.1. Beregn de symmetriske komponentene.*

Tabell 8.1: Data for trefasenettverk

E_R	$230\,\mathrm{V}\angle 0\,^\circ$
E_S	$200\,\mathrm{V}\angle -100\,^\circ$
E_T	$250\,\mathrm{V}\angle -250\,^\circ$
R	$50\,\Omega$



Figur 8.2: Trefasenettverk med usymmetriske spenninger og symmetrisk last

Løsning:
Det er i utgangspunktet vanskelig å beregne linjestrømmene da man ikke kjenner spenningsforskjellen mellom de to nullpunktene. De usymmetriske spenningene i tabell 8.1 kan dekomponeres til symmetriske komponenter som vist i påfølgende utregninger. Siden nullpunktene er isolerte, er det tilstrekkelig å beregne pluss- og minuskomponenten.

Plusspenninger:
$E_{R+} = \frac{1}{3}\left(230 + 200\angle\left(-100+120\right)\,^\circ + 250\angle\left(-250-120\right)\,^\circ\right) = 222\,\mathrm{V}\angle 2,2\,^\circ$
$E_{S+} = 222\,\mathrm{V}\angle\left(2,2-120\right)\,^\circ = 222\,\mathrm{V}\angle -117,8\,^\circ$
$E_{T+} = 222\,\mathrm{V}\angle\left(2,2-240\right)\,^\circ = 222\,\mathrm{V}\angle -237,8\,^\circ$

Minusspenninger:
$E_{R+} = \frac{1}{3}\left(230 + 200\angle\left(-100-120\right)\,^\circ + 250\angle\left(-250+120\right)\,^\circ\right) = 35\,\mathrm{V}\angle -143\,^\circ$
$E_{S+} = 35\,\mathrm{V}\angle\left(-143+120\right)\,^\circ = 35\,\mathrm{V}\angle -23\,^\circ$
$E_{T+} = 35\,\mathrm{V}\angle\left(-143+240\right)\,^\circ = 35\,\mathrm{V}\angle 97\,^\circ$

Hvis man påtrykker hver av spenningskomponentene ovenfor, blir strømkomponentene som følger:

Plusstrømmer:
$I_{R+} = \frac{222\angle 2{,}2\,^\circ}{50} = 4,44\,\mathrm{A}\angle 2,2\,^\circ$
$I_{S+} = \frac{222\angle -117{,}8\,^\circ}{50} = 4,44\,\mathrm{A}\angle - 117,8\,^\circ$
$I_{T+} = \frac{222\angle -237{,}8\,^\circ}{50} = 4,44\,\mathrm{A}\angle - 237,8\,^\circ$

Minusstrømmer:
$I_{R-} = \frac{35\angle -143\,^\circ}{50} = 0,7\,\mathrm{A}\angle - 143\,^\circ$
$I_{S-} = \frac{35\angle -23\,^\circ}{50} = 0,7\,\mathrm{A}\angle - 23\,^\circ$
$I_{T-} = \frac{35\angle 97\,^\circ}{50} = 0,7\,\mathrm{A}\angle 97\,^\circ$

Summerer en disse bidragene for hver fase, finner en de ubalanserte linjestrømmene:

$I_R = I_{R+} + I_{R-} = 4,44\angle 2,2\,^\circ + 0,7\angle - 143\,^\circ = 3,89\,\mathrm{A}\angle - 3,7\,^\circ$
$I_S = I_{S+} + I_{S-} = 4,44\angle - 117,8\,^\circ + 0,7\angle - 23\,^\circ = 4,44\,\mathrm{A}\angle - 109\,^\circ$
$I_T = I_{T+} + I_{T-} = 4,44\angle - 237,8\,^\circ + 0,7\angle 97\,^\circ = 5,08\,\mathrm{A}\angle - 241\,^\circ$

Dersom en har et fireledernettverk eller en også ønsker å se på jordingssystemer og jordfeilstrømmer, må en også ta med nullkomponenten i beregningene.

9 Mekaniske forhold

9.1 Drivmoment, lastmoment og treghetsmoment

En elektromotor vil ha et drivmoment T_{el} som får den til å gå rundt og et lastmoment (bremsemoment) T_{last} som prøver å bremse den. I tillegg kommer motorens friksjon, så det totale lastmomentet sett fra motoren $T_{last}{}'$ vil være summen av det egentlige lastmomentet og friksjonsmomentet T_{fr}, slik det er uttrykt i formel (9.1):

$$T_{last}{}' = T_{last} + T_{fr} \tag{9.1}$$

Forholdet mellom drivmomentet og det totale lastmomentet avgjør om motoren holder konstant turtall, eller hvorvidt det øker eller avtar. Størrelsen på den roterende massen (treghetsmomentet J) bestemmer hvor raskt en slik turtallsendring vil skje.
Hvor raskt en elektrisk maskin roterer, kan angis på to måter, enten i form av turtallet n (omdreininger per minutt) eller vinkelhastigheten ω (radianer per sekund). Siden begge størrelser beskriver mekanisk rotasjon, er de proporsjonale. Forholdet mellom turtall og vinkelhastighet er gitt i formel (9.2):

$$n = \frac{60}{2\pi}\omega = 9,55\omega \tag{9.2}$$

Forholdet mellom drivmoment, lastmoment, treghetsmoment og endring i rotasjonshastigheten sammenfattes i momentligningen:

$$J\frac{d\omega}{dt} = T_{el} - T_{last}{}' \tag{9.3}$$

Eksempel 1 *I et gitt driftstilfelle er drivmomentet* $T_{el} = 50\,\mathrm{N\,m}$, *Lastmomentet* $T_{last} = 30\,\mathrm{N\,m}$, *og friksjonsmomentet* $T_{fr} = 5\,\mathrm{N\,m}$. *Det samlede treghetsmomentet* $J = 0,20\,\mathrm{kg\,m^2}$. *Endrer motoren hastighet? Regn i såfall ut hastighetsendringen i* $\mathrm{rad/\,s^2}$.

Løsning:
Lastmomentet sett fra motoren er

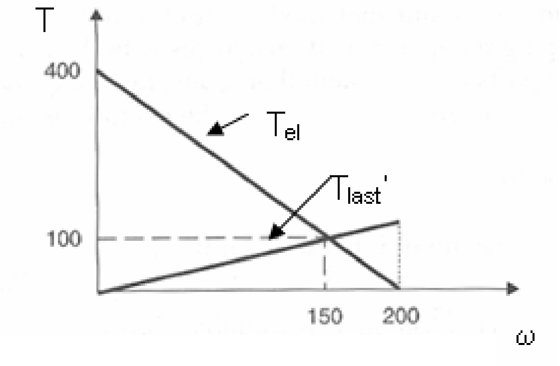
$$T_{last}{}' = T_{last} + T_{fr} = 30 + 5 = 35\,\mathrm{N\,m}$$

Siden drivmomentet er høyere enn lastmomentet, øker turtallet.
Hastighetsendringen er

$$\frac{d\omega}{dt} = \frac{T_{el} - T_{last}{}'}{J} = \frac{50 - 35}{0,20} = 75\,\mathrm{rad/\,s^2}$$

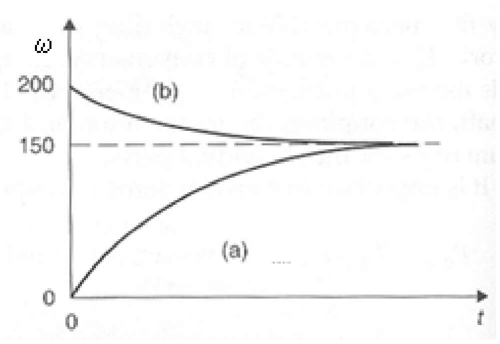
9.2 Arbeidspunkt

Figur 9.1 viser drivmoment og lastmoment som funksjon av motorens vinkelhastighet. En ser at drivmomentet avtar lineært med hastigheten og faller til null ved 200 rad/s. Lastmomentet øker derimot lineært med vinkelhastigheten. Ved en rotasjonshastighet på 150 rad/s er begge momentene like store, og høyre side i momentligningen blir null. Dermed må også endringen i vinkelhastighet være lik null, noe som betyr at motoren går med konstant hastighet. Dette skjæringspunktet er med andre ord et stabilt for motoren.



Figur 9.1: Drivmoment og lastmoment som funksjon av vinkelhastighet

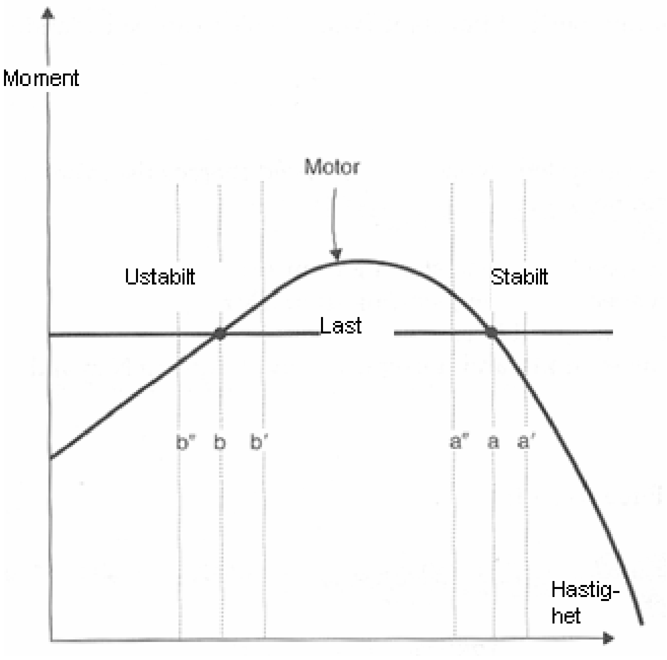
Dersom motoren går med 200 rad/s når lasten kobles inn, vil bremsemomentet være større enn drivmomentet, og den vil gå saktere. Dersom motoren derimot står stille (oppstart), vil drivmomentet være høyt, og den vil raskt dra seg opp i turtall. Disse to hastighetsforløpene er vist på figur 9.2. Kurve (a) viser hastighetsøkningen fra stillstand, og kurve (b) viser oppbremsingen fra 200 rad/s. I begge tilfelle endrer hastigheten på 150 rad/s. Vi legger dessuten merke til at hastighetsendringen tar like lang tid i begge tilfelle, fordi det er treghetsmomentet som avgjør hvor raskt den finner et stabilt turtall.



Figur 9.2: Hastighetsendringer for belastet motor

Noen ganger kan karakteristikkene for driv- og lastmoment skjære hverandre flere steder, slik det er vist på figur 9.3. I arbeidspunktet a er drivmoment og lastmoment være like store, og turtallet er da konstant. Skulle hastigheten av en eller annen grunn øke til a', vil bremsemomentet være større enn drivmomentet, og motoren vender tilbake til a. Skulle hastigheten falle til a", vil drivmomentet øke og bringe den tilbake til a, som med andre ord er et stabilt arbeidspunkt.
Dersom motorens hastighet tilsvarer arbeidspunktet b, vil også turtallet holde seg konstant, siden momentene er like store. Skulle hastigheten øke til b', vil motoren øke turtallet til den stabiliserer seg i punkt a. Skulle hastigheten avta til b", vil motoren gå saktere og saktere, inntil den stanser. Dette innbærer at b er et ustabilt arbeidspunkt.

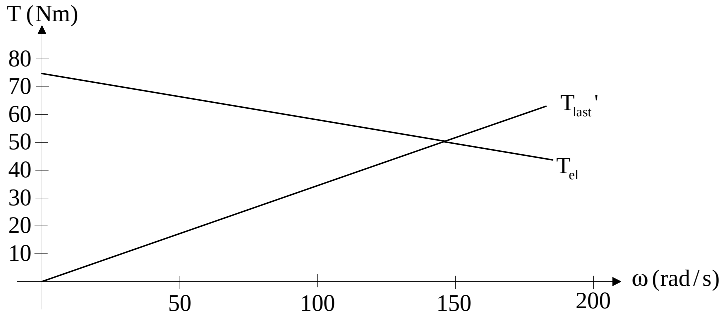
Eksempel 2 *Det totale lastmomentet for en motor er gitt ved* $T_{last}{}'(\omega) = 0,3\omega$. *Drivmomentet er* $T_{el}(\omega) = 75 - 0,2\omega$. *Treghetsmomentet er* $J = 0,4\,\mathrm{kg\,m^2}$. *Tegn moment/hastighetskarakteristikk for*



Figur 9.3: Stabilt og ustabilt arbeidspunkt

drivmoment og last i felles diagram. Regn ut moment og vinkelhastighet for motorens stabile arbeidspunkt. Beregn også turtallet i dette arbeidspunktet. Sett opp et uttrykk for motorens vinkelhastighet som funksjon av tiden.

Løsning:
Figur 9.4 viser begge momentkarakteristikkene i felles diagram.



Figur 9.4: Drivmoment og lastmoment i felles moment/hastighetsdiagram

Det stabile arbeidspunktet kjennetegnes ved at $T_{el} = T_{last}\,'$, som tilsvarer at $75 - 0,2\omega = 0,3\omega$. Vi løser denne ligningen med hensyn på ω:

$$\begin{aligned} 0,5\omega &= 75 \\ \omega &= 150\,\mathrm{rad/s} \end{aligned}$$

Momentet blir da

$$T = T'_{last} = 0,3 \cdot 150 = 45\,\mathrm{N\,m}$$

Vi ser at dette stemmer overens med arbeidspunktet på figur 9.4.
Turtallet er

$$n = 9,55 \cdot \omega = 9,55 \cdot 150 = 1430\text{o/min}$$

Hvis vi setter de to momentuttrykkene i momentligningen, får vi

$$0,4\frac{d\omega}{dt} = 75 - 0,2\omega - 0,3\omega = 75 - 0,5\omega$$

som er en 1. ordens differensialligning.
Denne kan også skrives som

$$\dot{\omega} + 1,25\omega = 187,5$$

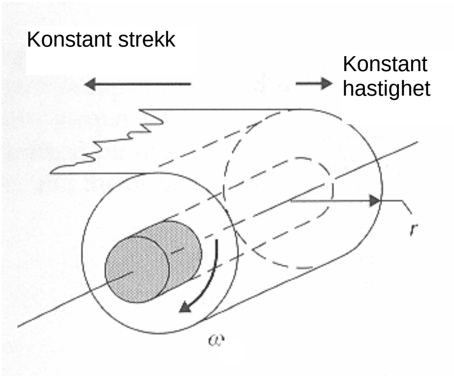
Tidsuttrykket blir

$$\omega = Ce^{-1,25t} + 150$$

som viser at vinkelhastigheten alltid går mot $150\,\mathrm{rad/\,s}$.

9.3 Ulike typer lastkarakteristikk

Konstant effekt
Last med konstant effekt kan for eksempel være en trommel for opprulling av papir eller tøy, hvor materialet rulles opp med konstant strekk og hastighet (se figur 9.5).

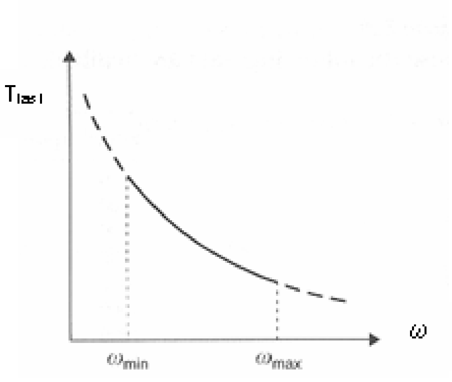


Figur 9.5: Trommel for opprulling av materiale

Lastmomentet vil naturligvis øke etter hvert som rullen vokser, siden dreiemomentet er lik kraft ganger radius. Vinkelhastigheten må avta, siden omkretsen øker. Forholdet mellom lastmoment og vinkelhastighet blir dermed

$$T_{last} = \frac{P_{last}}{\omega} \tag{9.4}$$

Dette omvendt proporsjonale forholdet er vist på figur 9.6.



Figur 9.6: Omvendt proporsjonalt forhold mellom moment og motorhastighet

Eksempel 3 *En papirmaskin vikler opp papirduk med konstant strekk* $F = 100\,\mathrm{N}$ *og konstant hastighet* $v = 1,5\,\mathrm{m/\,s}$. *Ved tom rull er radien* $r = 1,5\,\mathrm{m}$*; når rullen er full, er radien* $4,0\,\mathrm{m}$. *Regn ut lasteffekten. Regn dessuten ut lastmoment og vinkelhastighet ved tom rull og ved full rull.*

Løsning:
Lasteffekten er

$$P_{last} = F \cdot v = 100 \cdot 1,5 = 150\,\mathrm{W}$$

Lastmoment ved tom rull:

$$T_{last} = F \cdot r = 100 \cdot 1,5 = 150\,\mathrm{N\,m}$$

Vinkelhastighet ved tom rull:

$$\omega = \frac{v}{r} = \frac{1,5}{1,5} = 1,0\,\mathrm{rad/\,s}$$

Lastmoment ved full rull:

$$T_{last} = F \cdot r = 100 \cdot 4,0 = 400\,\mathrm{N\,m}$$

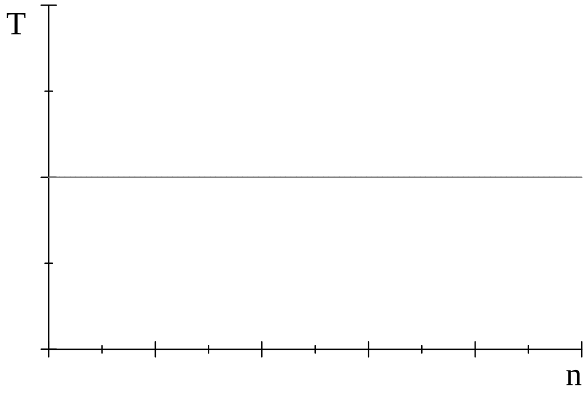
Vinkelhastighet ved full rull:

$$\omega = \frac{v}{r} = \frac{1,5}{4,0} = 0,375\,\mathrm{rad/\,s}$$

Konstant moment
Last med konstant moment kan for eksempel være transportbånd, heisekraner eller valseverk. Momentet vil være konstant og uavhengig av turtallet:

$$T_{last} = konst \tag{9.5}$$

I noen tilfeller (for eksempel et transportbånd) vil det være et høyere startmoment på grunn av friksjon.



Figur 9.7: Konstant lastmoment

Eksempel 4 *En heis har en trommel med radius* $r = 0,5\,\mathrm{m}$. *Heisen skal løfte en last på* $m = 500\,\mathrm{kg}$. *I et driftstilfelle løftes lasten med* $v = 2,0\,\mathrm{m/\,s}$. *Regn ut lastmomentet, vinkelhastigheten og turtallet på heistrommelen.*

Løsning:
Lasten gir en kraftvirkning

$$G = m \cdot g = 500 \cdot 9,8 = 4900\,\mathrm{N}$$

Lastmomentet er

$$T_{last} = G \cdot r = 4900 \cdot 0,5 = 2450\,\mathrm{N\,m}$$

Trommelens vinkelhastighet:

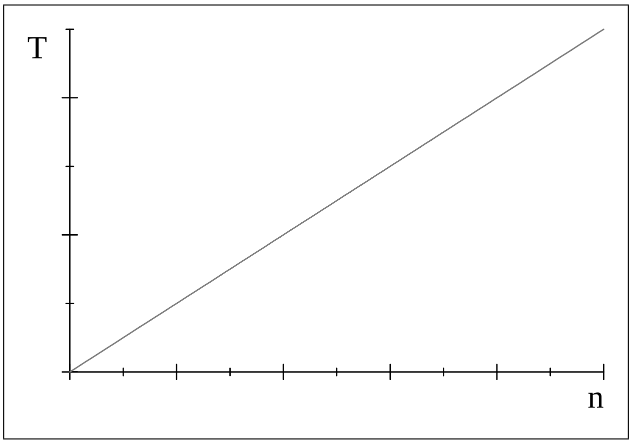
$$\omega = \frac{v}{r} = \frac{2,0}{0,5} = 4,0\,\mathrm{rad/\,s}$$

Turtallet er

$$n = 9,55 \cdot \omega = 38 \text{ o/min}$$

Lineært økende moment
Last med lineært økende moment kan være last med viskøs friksjon (for eksempel en anordning for å røre rundt i noe). Forholdet mellom lastmoment og motorhastighet er da gitt ved

$$T_{last} = k \cdot \omega \tag{9.6}$$



Figur 9.8: Lineært økende lastmoment

Eksempel 5 *En blandetrommel har et lastmoment* $T_{last} = 500\,\mathrm{N\,m}$ *ved* $5,0\,\mathrm{rad/\,s}$. *Hva blir lastmomentet ved* 120 *o/min?*

Løsning:
120 o/min tilsvarer en vinkelhastighet

$$\omega = \frac{120}{9,55} = 12,6\,\mathrm{rad/\,s}$$

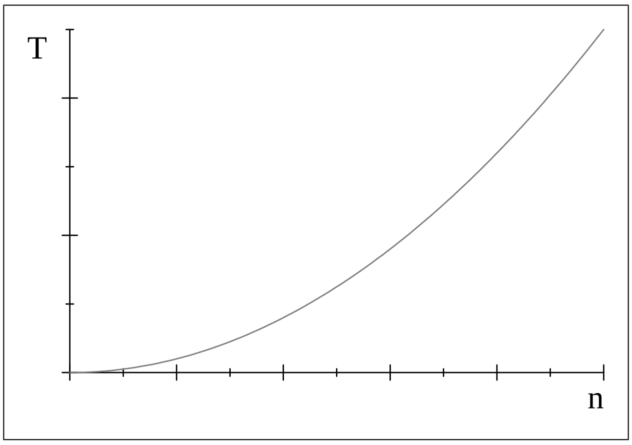
Dette gir et lastmoment

$$T_{last} = 500 \cdot \frac{12,6}{5,0} = 1260\,\mathrm{N\,m}$$

Kvadratisk økende moment
Last med kvadratisk økende moment er vanligvis vifter eller pumper. Forholdet mellom lastmoment og motorhastighet blir da

$$T_{last} = k \cdot \omega^2 \tag{9.7}$$

Eksempel 6 *En* $4,0\,\mathrm{kW}$ *vifte går med et turtall på* 950 *o/min. Regn ut lastmomentet. Hva hender med momentet dersom turtallet økes med* 30%*?*



Figur 9.9: Kvadratisk økende lastmoment

Løsning:
Vinkelhastigheten er

$$\omega = \frac{950}{9,55} = 99,5\,\mathrm{rad/\,s}$$

Lastmomentet er

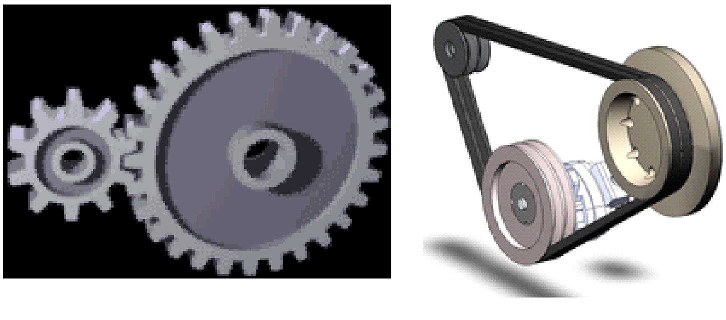
$$T_{last} = \frac{P}{\omega} = \frac{4000}{99,5} = 40,2\,\mathrm{N\,m}$$

Ved en turtallsøkning blir lastmomentet

$$T_{last,130} = T_{last,100}\left(\frac{130}{100}\right)^2 = 40,2 \cdot 1,3^2 = 67,9\,\mathrm{N\,m}$$

9.4 Utvekslinger

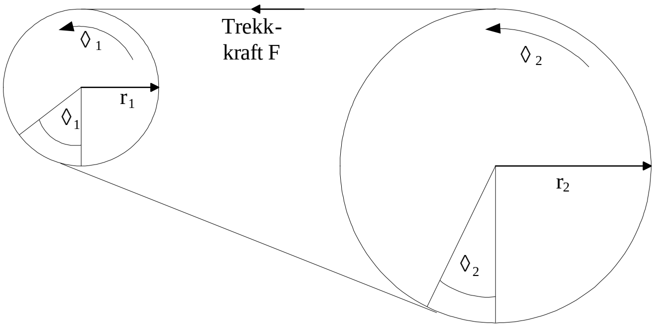
Noen ganger er det ikke hensiktsmessig å la den mekaniske lasten rotere med motorens hastighet. En karusell må naturligvis gå mye langsommere rundt enn motoren, og en kraftig sentrifuge trenger kanskje å gå raskere rundt. For å endre rotasjonshastigheten, brukes enten tannhjulsoverføringer (gir) eller remdrift. Disse systemene er vist på figur 9.10.



Figur 9.10: Systemer for endring av rotasjonshastighet og dreiemoment

Figur 9.11 viser en remdrift hvor forholdet mellom radiene er 1:2.
Trekkraften F vil være den samme på begge hjulene. Dersom det minste hjulet dreier en vinkel θ_1, vil det store hjulet dreie vinkelen θ_2. Forholdet mellom disse vinklene vil være gitt ved

$$\theta_2 = \frac{r_1}{r_2}\theta_1 \tag{9.8}$$



Figur 9.11: Omsetningsforhold for remdrift

Siden vinkelhastighet er vinkelforflytning per tidsenhet, vil forholdet mellom rotasjonshastighetene være

$$\omega_2 = \frac{r_1}{r_2}\omega_1 \tag{9.9}$$

som tilsier at det store hjulet roterer halvparten så fort som det lille.
Trekkraften F kan skrives som

$$F = \frac{T_1}{r_1} = \frac{T_2}{r_2} \tag{9.10}$$

som gir følgende forhold mellom dreiemomentene:

$$T_2 = \frac{r_2}{r_1}T_1 \tag{9.11}$$

Effektomsetningen er

$$P_1 = \omega_1 T_1 = \omega_2 T_2 = P_2 \tag{9.12}$$

som gir at avgitt effekt er lik tilført effekt.
Hvis man ”ser” treghetsmomentet for det store hjulet fra det lille, blir forholdet

$$J_2{}' = \left(\frac{r_1}{r_2}\right)^2 J_2 \tag{9.13}$$

Eksempel 7 *To tannhjul står i inngrep med hverandre. Det minste tannhjulet er tilkoblet en elektromotor, mens det største er tilkoblet en roterende last. Når det minste tannhjulet har gjort ett omløp, har det store dreid rundt* $0,628\,\mathrm{rad}$. *Når lasten roterer med* 150 *o/min ved konstant turtall, er motorens drivmoment* $20\,\mathrm{N\,m}$. *Lasten har et treghetsmoment på* $50\,\mathrm{kg\,m^2}$. *Regn ut lasteffekten, samt lastens treghetsmoment sett fra motorsiden. Se bort fra tap i systemet.*

Løsning:
Omsetningsforholdet er

$$\frac{r_1}{r_2} = \frac{\theta_2}{\theta_1} = \frac{0,628}{2\pi} = 0,10$$

Lastens vinkelhastighet er

$$\omega_{last} = \frac{150}{9,55} = 15,7\,\mathrm{rad/\,s}$$

Motorens vinkelhastighet er

$$\omega_{motor} = \frac{\omega_{last}}{0,1} = \frac{15,7}{0,1} = 157\,\mathrm{rad/\,s}$$

Hvis vi ser bort fra tapene, vil $P_{last} = P_{motor}$. Dette gir

$$P_{last} = P_{motor} = T_{el} \cdot \omega_{motor} = 20 \cdot 157 = 3140\,\mathrm{W}$$

Treghetsmomentet sett fra motorsiden er

$$J_{last}{}' = J_{last} \cdot \left(\frac{r_1}{r_2}\right)^2 = 50 \cdot 0,1^2 = 0,50\,\mathrm{kg\,m^2}$$

9.5 Translatoriske systemer (rettlinjet bevegelse)

Noen ganger gir en motor drivkraft til en rettlinjet bevegelse, for eksempel en heis eller et transportbånd. Formel (9.3) har da sin parallell i en av Newtons bevegelsesligninger:

$$m\frac{dv}{dt} = F_{el} - (F_{last} + F_{fr}) = F_{el} - F_{last}{}' \tag{9.14}$$

hvor m er systemets samlede masse
F_{el} er den rettlinjede drivkraften frembrakt av elektromotoren
F_{last} er lastens bremsekraft i motsatt retning av drivkraften, inklusive tap i lasten
F_{fr} er det krafttapet som skyldes friksjonen i motoren
$F_{last}{}'$ er den ekvivalente bremsekraften fra last og motorfriksjon
v er hastigheten for den rettlinjede bevegelsen
Motoren leverer en elektromagnetisk effekt som er gitt ved

$$P_{el} = F_{el} \cdot v \tag{9.15}$$

Lasten opptar en effekt som er gitt ved

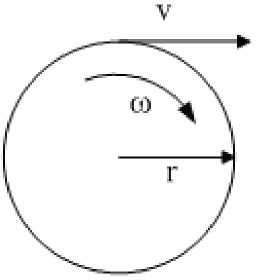
$$P_{last} = F_{last} \cdot v \tag{9.16}$$

Friksjonstapene i motoren tilsvarer

$$P_{fr} = F_{fr} \cdot v \tag{9.17}$$

Figur 9.12 viser sammenhengen mellom vinkelhastigheten ω og den translatoriske hastigheten v. Forholdet mellom disse to størrelsene er gitt ved

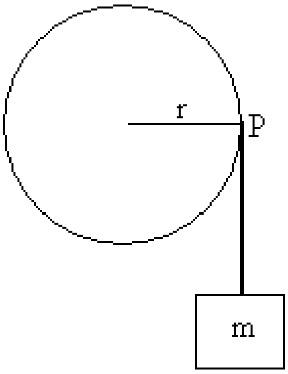
$$v = \omega \cdot r \tag{9.18}$$



Figur 9.12: Roterende og rettlinjet bevegelse i overgangen mellom et roterende og et translatorisk system

Dersom en masse m virker mot et punkt P, slik det er vist på figur 9.13, kan treghetsmomentet for punktmassen beregnes som vist i (9.19).

$$J_m = m \cdot r^2 \tag{9.19}$$

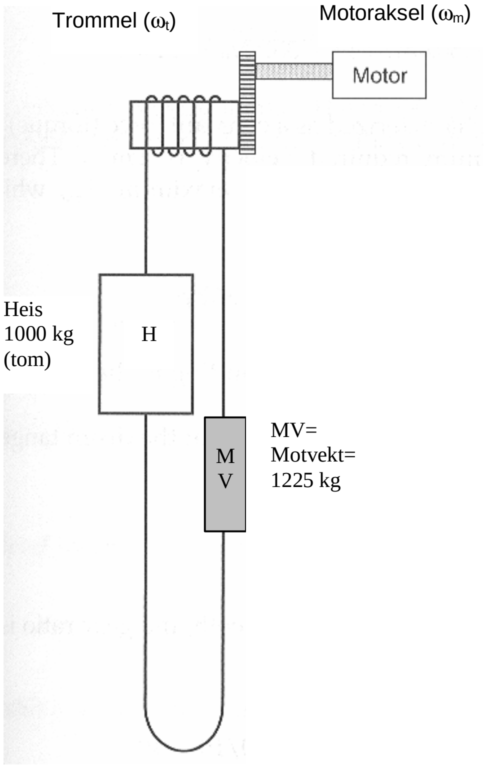


Figur 9.13: Virkning av punktmasse på et hjul

9.6 Heisdrift (illustrerende eksempel)

Figur 9.14 viser en heisdrift med en motor, en girutveksling, en trommel for heiswiren, en heis og en motvekt.
Følgende data er gitt:
Giret har en utveksling på $1/40$
Trommelen er en hul ståltrommel med følgende mål:
Lengde: 150 cm
Radius: 40 cm
Tykkelse: 5 cm
Tetthet: 8 kg/dm^3
Heiswire:
Vekt: $0,8$ kg/m
Bruddstyrke: 30 kN

Lengde: 102 m
Ytelse:
Kapasitet: 15 passasjerer á 75 kg
10 etasjer med 4 m avstand
Toppfart (opp og ned) 2 m/s



Figur 9.14: Heisdrift

Noen ganger vil lasten på grunn av vektfordelingen prøve å trekke motoren rundt, og da vil motoren gå i generatordrift. Andre ganger må motoren yte en trekkraft for å flytte lasten i ønsket retning og går da i motordrift. Når heisen skal gå i en retning, går motoren i foroverretning. Når heisen går i motsatt retning, må motoren gå baklengs. Tabell 9.1 viser en sammenheng mellom antall passasjerer, heisretning og motorens driftsform.

Tabell 9.1: Passasjerantall, retning og driftsform

Antall passasjerer	Retning	Motorens driftsform
1 – 2	Opp	Generator forlengs
3	Opp	Tomgang forlengs
4 – 15	Opp	Motor forlengs
1 – 2	Ned	Motor baklengs
3	Ned	Tomgang baklengs
4 – 15	Ned	Generator baklengs

Massevirkningen av passasjerer, heis og motvekt blir

$$\sum m = m_{heis} + 75 \cdot N_p - m_{motvekt} = 75 \cdot n_p - 225 \tag{9.20}$$

hvor N_p er antall passasjerer.

Det gir følgende kraftvirkning fra lasten:

$$F_{last} = G = \sum m \cdot g = (75 \cdot N_p - 225) \cdot 9,81 \tag{9.21}$$

Maksimal lastkraft kreves ved full heis (15 personer):

$$F_{last,\max} = (75 \cdot 15 - 225) \cdot 9,81 = 8830\,\mathrm{N} \tag{9.22}$$

Denne type last har konstant moment som er uavhengig av hastigheten. Topphastigheten er 2,0 m/s. Maksimal lasteffekt vil da bli

$$P_{last,\max} = F_{last,\max} \cdot v_{\max} = 8830 \cdot 2,0 = 17,7\,\mathrm{kW} \tag{9.23}$$

Det ville være naturlig å velge en motor på 20 kW.
Trommelens maksimale vinkelhastighet vil være

$$\omega_{t,\max} = \frac{v_{\max}}{r_t} = \frac{2,0}{0,4} = 5,0\,\mathrm{rad/\,s} \tag{9.24}$$

Med en girutveksling på 40:1, blir motorens maksimale vinkelhastighet

$$\omega_{m,\max} = 40 \cdot \omega_{t,\max} = 5,0 \cdot 40 = 200\,\mathrm{rad/\,s} \tag{9.25}$$

som tilsvarer et maksimalt motorturtall $n_{m,\max}$ på

$$n_{m,\max} = \omega_{m,\max} \cdot \frac{60}{2\pi} = 200 \cdot \frac{60}{2\pi} = 1910 \text{ o/min} \tag{9.26}$$

Maksimalt lastmoment på trommelen er

$$T_{last,\max} = F_{last,\max} \cdot r_t = 8830 \cdot 0,4 = 3,53\,\mathrm{kN\,m} \tag{9.27}$$

Motorens maksimale drivmoment må da være

$$T_{el,\max} = \frac{T_{last,\max}}{40} = \frac{3,53\,\mathrm{kN}}{40} = 88,3\,\mathrm{N\,m} \tag{9.28}$$

Massen av de ulike delene i bevegelse er
m_h = heismasse = 1000 kg
m_p = (maksimal) passasjermasse = 1125 kg
m_{mv} = massen av motvekten = 1225 kg
m_w = massen av heiswiren = $81,6$ kg
Trommelmassen er gitt ved

$$m_t = \rho \cdot \ell \cdot \pi \left(r_{ytre}^2 - r_{indre}^2\right) = 8000 \cdot 1,5 \cdot \pi \left(0,4^2 - 0,35^2\right) = 1414\,\mathrm{kg} \tag{9.29}$$

Summen av massen av de delene som er i translatorisk bevegelse er

$$\sum m = m_h + m_p + m_{mv} + m_w = 1000 + 1125 + 1225 + 81,6 = 3432\,\mathrm{kg} \tag{9.30}$$

Denne massen utgjør følgende treghetsmoment på trommelen:

$$J_{\Sigma m} = \sum m \cdot r_t^2 = 3432 \cdot 0,4^2 = 549\,\mathrm{kg\,m^2} \tag{9.31}$$

I henhold til treghetsmomentet for en hul sylinder, vil trommelen ha følgende treghetsmoment:

$$J_t = \tfrac{1}{2} \cdot m_t \cdot \left(r_{ytre}^2 + r_{indre}^2\right) = 0,5 \cdot 1414 \cdot \left(0,4^2 + 0,35^2\right) = 200\,\mathrm{kg\,m^2} \tag{9.32}$$

Det totale treghetsmomentet for lasten blir dermed

$$J_{last} = J_{\Sigma m} + J_t = 549 + 200 = 749 \text{ kg m}^2 \tag{9.33}$$

Sett fra motorakselen vil lastmomentet utgjøre

$$J_{last}' = \frac{J_{last}}{40^2} = \frac{749}{40^2} = 0{,}468 \text{ kg m}^2 \tag{9.34}$$

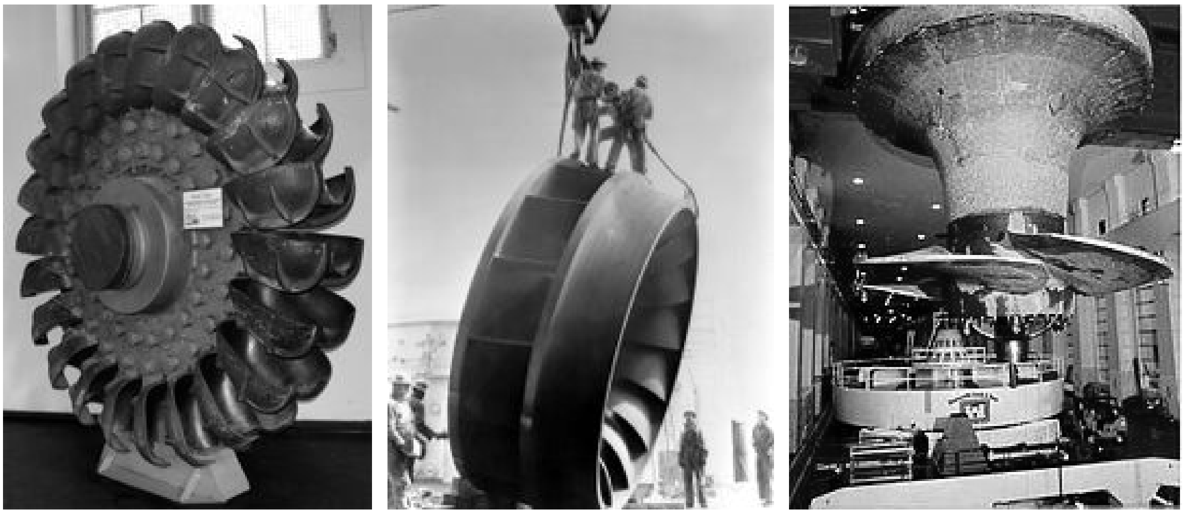
Går vi ut fra at treghetsmomentet til en 20 kW motor er $J_{el} = 0,25$ kg m^2, blir det totale treghetsmomentet for motor og last

$$J_{tot} = J_{el} + J_{last}' = 0{,}25 + 0{,}468 = 0{,}718 \text{ kg m}^2 \tag{9.35}$$

Massen av lasten gir med andre ord nesten en tredobling av motorens treghetsmoment.

9.7 Turbiner og drivmotorer

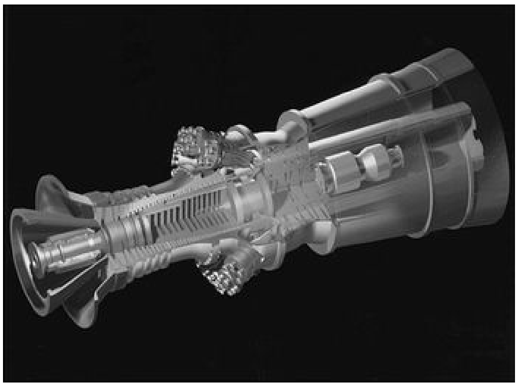
En roterende elektrisk maskin kan både drives som motor og generator. Ønsker man å bruke en roterende elektrisk maskin som generator, må det tilføres mekanisk effekt på akselen, og denne effekten må genereres av en turbin eller en drivmotor.
Den mest vanlige turbintypen i Norge er vannkraftturbinen (figur 9.15). Fra venstre mot høyre på figuren vises løpehjulene til en Peltonturbin (høye fallhøyder), en Francisturbin (midlere fallhøyder og en Kaplanturbin (lave fallhøyder, elvekraftverk). Vannturbiner kan levere konstant effekt, men tåler også raske effektvariasjoner. Vannturbiner har en virkningsgrad på over 90 %.



Figur 9.15: Løpehjul for ulike typer vannkraftturbiner

På norske oljeinstallasjoner og store skip brukes en annen type turbiner, nemlig dampturbiner. Løpehjulet til en slik er vist på figur 9.16. Damp produseres ved hjelp av fossilt brensel, fisjon, jordvarme eller solvarme, og det høye damptrykket setter turbinen i bevegelse. Dampturbiner brukes bare for høye ytelser, og for å unngå materialspenninger på grunn av oppvarming og avkjøling bør de gå med konstant effekt og temperatur. En stor dampturbin har en virkningsgrad på omtrent 40 %.
En mindre turbintype er gassturbinen, og den brukes også mye offshore og på skip. Figur 9.17 viser en gjennomskåret gassturbin. I motsetning til dampturbinen, hvor en varmekilde skaper trykk i vanndamp, drives gassturbinen av trykket i avgassene ved en forbrenningsprosess. Turbinen er koblet til

Figur 9.16: Løpehjulet til en dampturbin

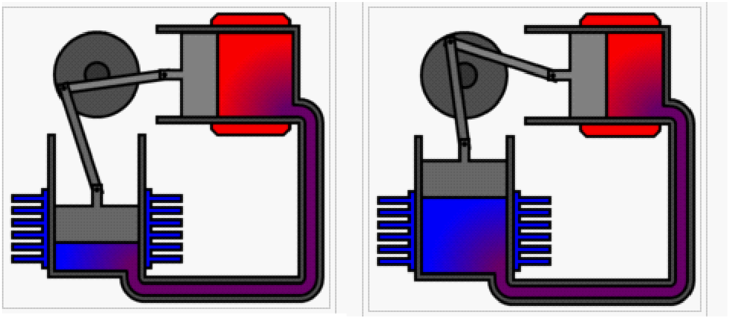


Figur 9.17: Gassturbin

en kompressor som komprimerer innsugingsluften og fører den inn i et brennkammer hvor det tilføres brennstoff, og eksosgassene driver turbinen rundt. I likhet med dampturbinen bør gassturbinen levere relativt konstant effekt. Virkningsgraden for en gassturbin ligger på rundt 35 %.
Vindturbiner har blitt ganske vanlige i Norge i de senere årene, og de største turbinene leverer 5 MW. Figur 9.18 viser en moderne vindturbin. Det vanlige i dag er horisontalakslede turbiner med tre rotorblad. En vindturbin har en teoretisk øvre grense for virkningsgraden på $59,3$ %. Effektproduksjonen vil være intermitterende. Det vil si at den vil variere mye, siden vindstyrken hele tiden varierer. Vindproduksjon bør kombineres med vannkraft, siden vannkraften kan utreguleres hurtig.
Generatorer kan også drives av forbrenningsmotorer. Det mest vanlige i dag er dieselmotorer som finnes i mange størrelser og utførelser. For mindre anlegg kan Stirling-motoren være et alternativ. Figur 9.19 viser en prinsippskisse for en Stirling-motor. I oppvarmingsfasen befinner det seg mye gass i den varme sylinderen. Gassvolumet øker, og stemplene flytter seg slik at det totale stempelvolumet blir maksimalt. Resultatet er at det befinner seg mye gass i den kalde sylinderen, og gassen trekker seg sammen. Stemplene forsøker da å minimere gassvolumet. Underveis presses noe gass inn i den varme sylinderen, og hele syklusen gjentar seg.

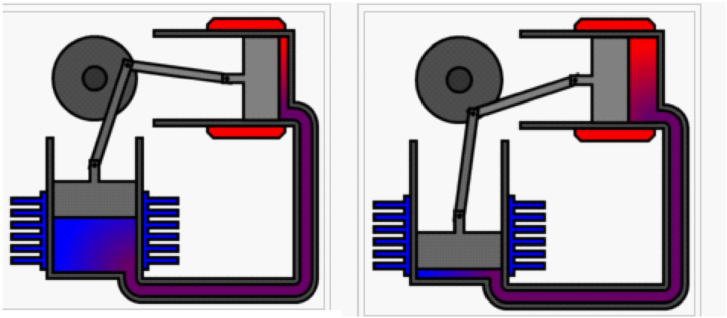
Motoren har et ytre brennkammer, samt et kjølesystem, og dette gjør at den er stillegående. Forbrenningen er fullstendig, og derfor vil den forurense mye mindre enn en eksplosjonsmotor.
Stirling-motoren har dårlig dynamikk og egner seg derfor best til konstant drift. Den har ikke startmoment, så ved oppstart må generatoren brukes som startmotor.

Figur 9.18: Horisontalakslet vindturbin med en effekt på 2 MW



Oppvarming

Utvidelse



Avkjøling

Sammentrekning

Figur 9.19: Virkemåte for Stirling-maskin

9.8 Øvingsoppgaver

1. En roterende last har i et driftstilfelle et bremsemoment på $10\,\mathrm{N\,m}$. I tillegg utgjør motorens friksjonsmoment $2,0\,\mathrm{N\,m}$ i dette tilfellet. Motoren har et drivmoment på $16\,\mathrm{N\,m}$, og motorens treghetsmoment er $0,20\,\mathrm{kg\,m^2}$. Lasten har et treghetsmoment på $0,35\,\mathrm{kg\,m^2}$. Vil systemet endre vinkelhastighet? Hvor stor vil denne endringen i så fall bli?

2. En last (inklusive friksjon) har karakteristikk som oppgitt i (9.36). Også karakteristikken for motorens drivmoment er gitt i (9.36). Finn systemets stabile arbeidspunkt. Hvilken vinkelhastighet tilsvarer dette?
$$\begin{aligned} T'_{last} &= 0,02n \\ T_{el} &= -0,0000233n^2 + 0,0183n + 25 \end{aligned} \tag{9.36}$$

3. Hvilken type last benyttes i oppgave 2?

4. En motor med merketurtall lik 2850 o/min skal drive en last med et turtall på 150 o/min. Ved dette turtallet har lasten et moment på $380\,\mathrm{N\,m}$. Det totale friksjonsmomentet sett fra motoren er $5\,\mathrm{N\,m}$. Motoren har et treghetsmoment på $0,25\,\mathrm{kg\,m^2}$, giret har et treghetsmoment sett fra motorakselen på $0,2\,\mathrm{kg\,m^2}$, og lasten har et treghetsmoment på $70\,\mathrm{kg\,m^2}$. Beregn girets omsetningsforhold, det totale lastmomentet sett fra motorakselen, samt det totale treghetsmomentet sett fra motorakselen.

5. En heistrommel med ytre radius $0,5\,\mathrm{m}$ løfter en last på $500\,\mathrm{kg}$ ved en wire som rulles opp på trommelen. Lasten heises opp med en hastighet på $0,75\,\mathrm{m/\,s}$. Tyngdeaksellerasjonen settes til $9,81\,\mathrm{m/\,s^2}$. Hvor stor effekt må tilføres trommelen for å foreta løftet? Hvilket lastmoment ligger på heistrommelens aksel? Hvilken vinkelhastighet må trommelen ha, og hvilket turtall tilsvarer det?

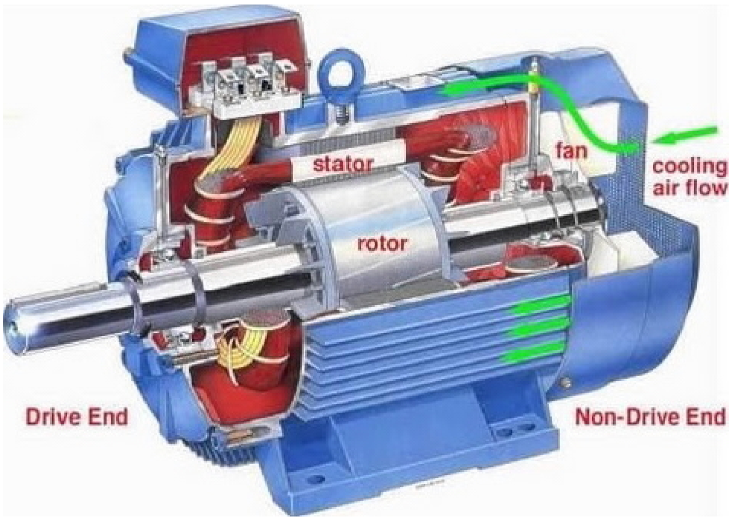
6. En generator omformer mekanisk energi til elektrisk energi. Hvor kommer den mekaniske energien fra?

10 Asynkronmaskinen

10.1 Utførelse og virkemåte

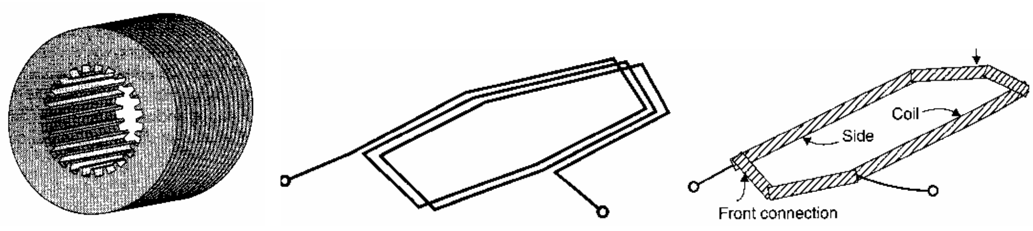
De tre mest vanlige roterende elektriske maskiner er synkronmaskinen, asynkronmaskinen og kommutatormaskinen. Synkronmaskinen og asynkronmaskinen er vanligvis trefase vekselstrømsmaskiner. Synkronmaskinen går med et konstant turtall som er bestemt av nettfrekvensen. Asynkronmaskinen går med et turtall som er høyere eller lavere enn det nettfrekvensen tilsier. Alle roterende elektriske maskiner kan i prinsipp både gå som motor og generator. Synkronmaskiner kan også brukes som fasekompensatorer.

Enhver roterende elektrisk maskin består av en stillestående (statisk) del – stator, og en roterende del (rotor). Figur 10.1 viser en gjennomskåret asynkronmaskin. I midten ser en rotoren og akselen med påmontert kjølevifte. Rundt rotoren ligger statoren med tilhørende viklinger. Ytterst ligger motorhuset med festebrakett, kjøleribber og tilkoblingsklemmer.



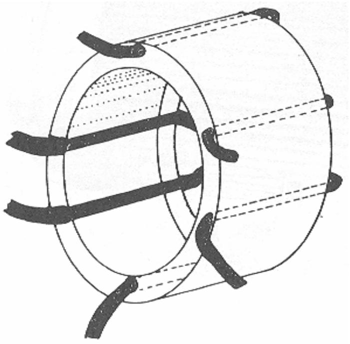
Figur 10.1: Gjennomskåret asynkronmaskin

Til venstre på figur 10.2 vises statorjernet, som består av mange lag blikk med spor som statorviklingene legges ned i. I midten og til høyre på figuren vises en enkelt vikling.



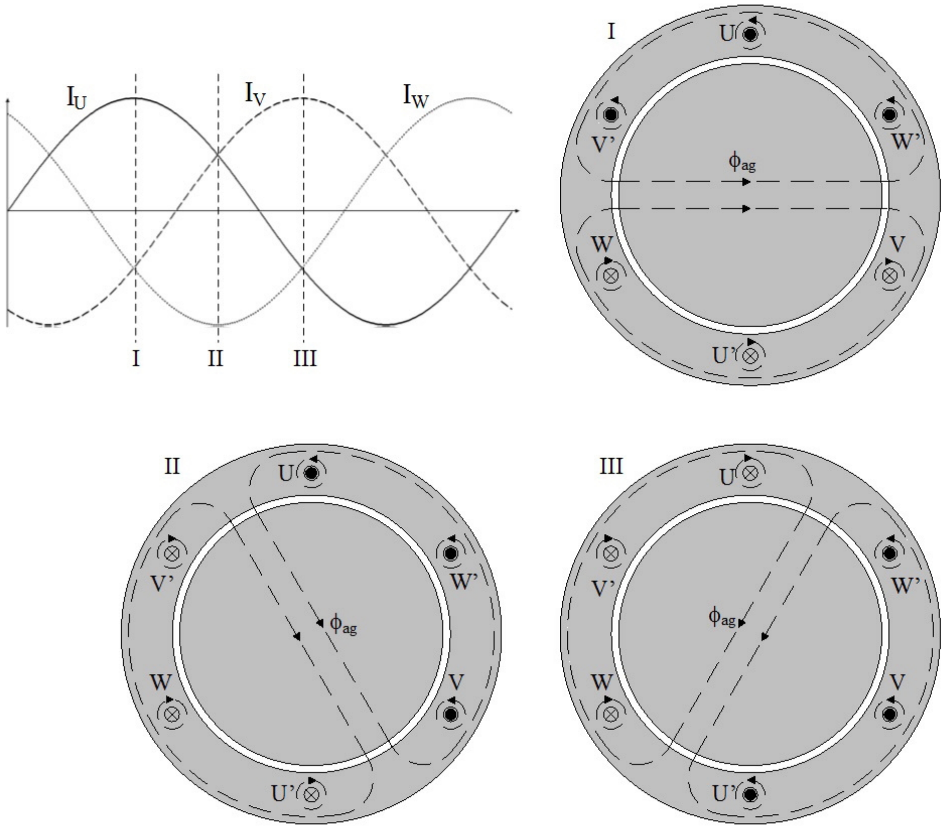
Figur 10.2: Statorblikk og statorvikling

Dersom hver fase kun inneholder en vikling, som vist på figur 10.3, vil hver vikling ligge diametralt over stator. Da vil stator ha ett par magnetpoler per fase, og vi sier at maskinen har ett polpar. De tre fasestrømmene i statorviklingene vil hele tiden ligge $120°$ faseforskjøvet i forhold til hverandre. Summen av de tre magnetfeltene vil danne et magnetfelt som går gjennom stator og rotor og over luftgapet mellom dem. Dette feltet kalles maskinens luftgapsfelt og er merket ϕ_{ag} (ag står for air gap).



Figur 10.3: Plassering av statorviklinger

Etter hvert som vekselstrømmene endrer størrelse og retning, vil dette luftgapsfeltet rotere rundt. Dette er vist på figur 10.4.



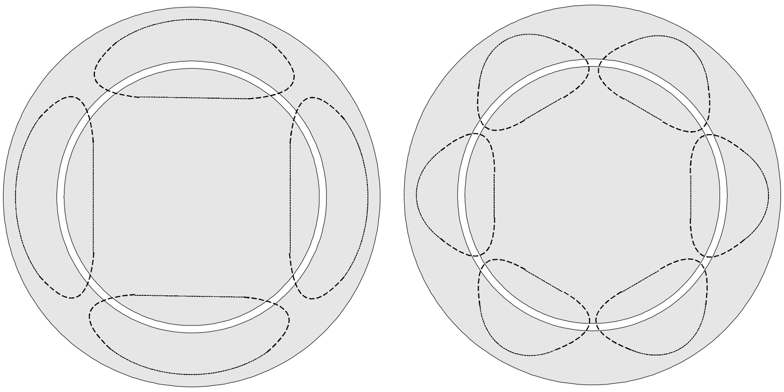
Figur 10.4: Roterende luftgapsfelt

Dersom hver fase består av flere viklinger, vil maskinen også ha flere polpar. Dette er vist på figur 10.5. Forholdet mellom antall polpar p, statorfrekvensen f_1 og luftgapsfeltets turtall n_s er gitt ved formel (10.1):

$$n_s = \frac{60 \cdot f_1}{p} \tag{10.1}$$

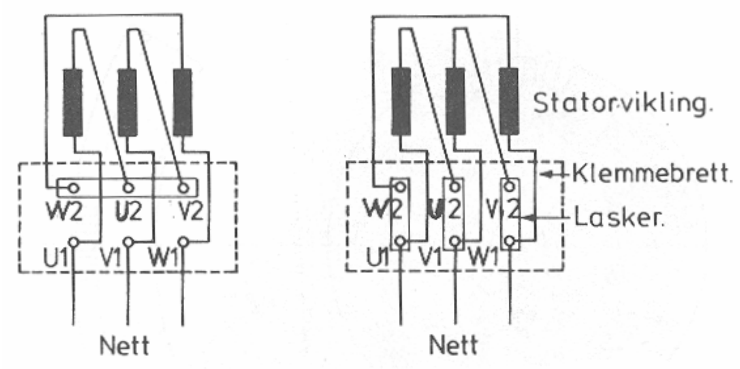
Det synkrone feltets vinkelhastighet er tilsvarende gitt ved (10.2):

$$\omega_s = \frac{2\pi f_1}{p} \tag{10.2}$$



Figur 10.5: Luftgapsfluks med to polpar (venstre) og tre polpar (høyre)

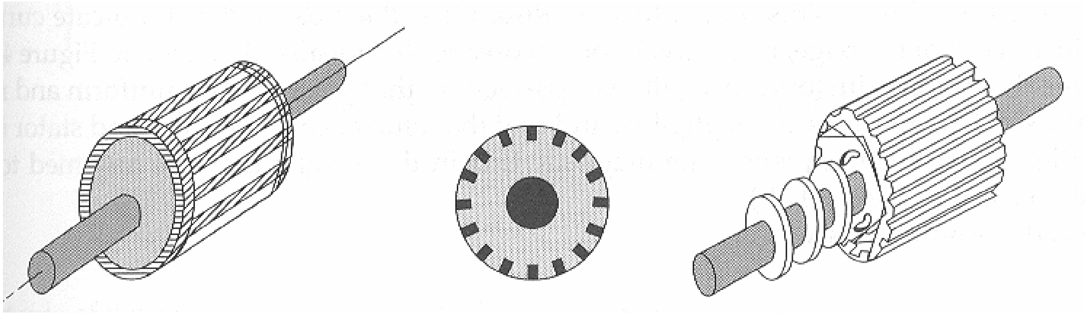
Viklingene kobles enten i stjerne eller trekant. Figur 10.6 viser et typisk klemmebrett for en asynkronmaskin. Ved å flytte på laskene mellom tilkoblingsklemmene, kan en velge hvilken trefasekobling en vil benytte.



Figur 10.6: Klemmebrett med y-koblet statorvikling (venstre) og d-koblet vikling (høyre)

10.2 Rotortyper

Asynkronmaskinen har to typer rotor, som vist på figur 10.7. Den vanligste typen er vist til venstre på figuren og kalles en burviklet rotor, fordi viklingene og endeflatene kan minne om et roterende hamsterbur. Viklingene er lagt ned i spor i jernblikkene, som vist på figuren i midten. Figuren til høyre viser en viklet rotor med sleperinger. Her legges y-koblede trefaseviklinger i sporene på rotoren, og endepunktene kobles til de tre sleperingene. Rotoren kobles til en ytre krets ved hjelp av børster og et klemmebrett med tilkoblingspunkter. Den burviklede rotoren har enklest oppbygning og krever ingen børster og en ytre strømkrets. Sleperingsrotoren gir imidlertid mulighet for å regulere rotorresistansen, samt å hente ut effekt fra rotorkretsen, effekt som ellers ville gitt strømvarmetap.



Figur 10.7: Rotortyper. Burviklet rotor (til venstre og i midten), viklet rotor med sleperinger (til høyre)

Når det roterende magnetfeltet skjærer rotorlederne, induseres det en spenning over disse, gitt ved formel (10.3):

$$e = B \cdot \ell \cdot v \tag{10.3}$$

hvor e er indusert spenning, B er flukstettheten, ℓ er effektiv lederlengde, og v er lederens hastighet vinkelrett på feltet.

Rotorlederne er som regel kortsluttede. Siden de har en lav resistans, vil de allerede ved en moderat spenning føre en betydelig strøm. En strømførende leder i et magnetfelt vil bli utsatt for en sideveis kraftvirkning, gitt ved formel (10.4):

$$F = B \cdot i \cdot \ell \tag{10.4}$$

hvor F er kraftvirkningen på en enkelt rotorleder, og i er strømmen i lederen.
Denne kraften er opphav til et drivmoment, gitt ved

$$T_{leder} = F \cdot r_2 \tag{10.5}$$

hvor T_{leder} er drivmomentet for en enkelt leder og r_2 er rotorradien.
Motorens elektrodynamiske drivmoment vil være summen av enkeltmomentene:

$$T_{el} = \sum T_{leder} = k \cdot B_{12} \cdot i_2 \tag{10.6}$$

hvor i_2 er rotorstrømmen og B_{12} er luftgapsfeltets flukstetthet.
Siden bare flukstettheten og rotorstrømmen er variable størrelser, kan en dra følgende slutninger av formel (10.6):

$$T_{el} = k \cdot \phi_{ag} \cdot I_2 \tag{10.7}$$

Det elektrodynamiske momentet vil med andre ord være proporsjonalt med både luftgapsfluksen og med rotorstrømmen. Dette momentet virker i samme retning som det roterende dreiefeltet og får motoren til å dreie rundt. Dersom rotor har samme vinkelhastighet som feltet, vil ikke lederne i rotor skjære feltlinjene, og det utvikles ikke noe moment. Motoren må gå saktere enn feltet (asynkron drift) for at det skal utvikles drivmoment. Dersom rotoren roterer raskere enn luftgapsfeltet, vil dreiemomentet skifte fortegn, og motoren vil utvikle et bremsemoment på akselen. Den vil da gå som generator.

Eksempel 1 *En asynkronmotor med to polpar er tilkoblet et* $50\,\mathrm{Hz}$ *nett. Rotor har en radius på* $15\,\mathrm{cm}$. *Ved et motorturtall på* 1450 *o/min utvikler motoren et drivmoment på* $40\,\mathrm{N\,m}$. *Regn ut feltets og rotorledernes hastighet langs luftgapet. Hvilket drivmoment har motoren ved* 1500 *o/min og ved* 1600 *o/min?*

Løsning:
Feltets vinkelhastighet er

$$\omega_s = \frac{2\pi f_1}{p} = \frac{2\pi \cdot 50}{2} = 157\,\mathrm{rad/\,s}$$

Tangenthastigheten langs luftgapet blir da

$$v_s = \omega_s \cdot r = 157 \cdot 0,15 = 23,6\,\mathrm{m/\,s}$$

Rotors vinkelhastighet er

$$\omega_r = \frac{1450}{9,55} = 152\,\mathrm{rad/\,s}$$

Rotorledernes tangenthastighet er

$$v_r = \omega_r \cdot r = 22,8\,\mathrm{m/\,s}$$

Rotorlederne skjærer altså feltet med en hastighet

$$v = v_s - v_r = 23,6 - 22,8 = 0,8\,\mathrm{m/\,s}$$

På bakgrunn av formel (10.3) og (10.4) ser vi at drivmomentet må være proporsjonalt med den hastigheten rotorlederne skjærer feltet med:

$$\begin{aligned} T_{el} &= k \cdot v \\ k &= \frac{T_{el}}{v} = \frac{40}{0,8} = 50 \end{aligned}$$

Ved et turtall på 1500 o/min blir vinkelhastigheten og tangenthastigheten:

$$\begin{aligned} \omega_r &= \frac{1500}{9,55} = 157\,\mathrm{rad/\,s} \\ v_r &= 157 \cdot 0,15 = 23,6\,\mathrm{m/\,s} \end{aligned}$$

Rotorlederne skjærer ikke feltet, men følger feltet:

$$v = 23,6 - 23,6 = 0\,\mathrm{m/\,s}$$

Det utvikles ikke noe drivmoment, siden motoren går med synkront turtall.
Ved et turtall på 1600 o/min blir vinkelhastigheten og tangenthastigheten:

$$\begin{aligned} \omega_r &= \frac{1600}{9,55} = 168\,\mathrm{rad/\,s} \\ v_r &= 168 \cdot 0,15 = 25,2\,\mathrm{m/\,s} \end{aligned}$$

Rotorlederne skjærer feltet med

$$v = 23,6 - 25,2 = -1,6\,\mathrm{m/\,s}$$

Drivmomentet blir

$$T_{el} = 50 \cdot (-1,6) = -80\,\mathrm{N\,m}$$

Siden rotor går fortere enn feltet (oversynkront turtall), vil motoren gi et bremsemoment og ikke et drivmoment. Den går i generatordrift.

10.3 Spenninger og omsetningsforhold

I likhet med transformatoren har også roterende elektriske maskiner to sett viklinger som deler en felles fluks, i dette tilfelle luftgapsfluksen. Også for asynkronmaskinen kan en snakke om sterkt koblede spoler. Strømmer og spenninger i rotorkretsen påvirker statorkretsen, og omvendt.

Figur 10.8 viser øverst luftgapet ”brettet ut”. På grunn av at statorvindingene er lagt i jevnt fordelte spor, vil de drivende amperevindingene (den magnetomotoriske kraften) ha en trappeform (nedre del av figuren). Luftgapet i seg selv gjør imidlertid at fluksen over luftgapet vil få en mer sinusformet fordeling. Derfor begår vi ingen stor feil om vi benytter transformatorligningen for å uttrykke indusert spenning per fase.

Indusert fasespenning i statorkretsen blir da

$$E_{1f} = 4,44 \cdot f_1 \cdot N_1 \cdot \phi_{\text{max}} \tag{10.8}$$

hvor f_1 er statorfrekvensen (nettfrekvens eller omformerfrekvens), N_1 er effektivt vindingstall per statorfase og ϕ_{max} er maksimal luftgapsfluks per poldeling.

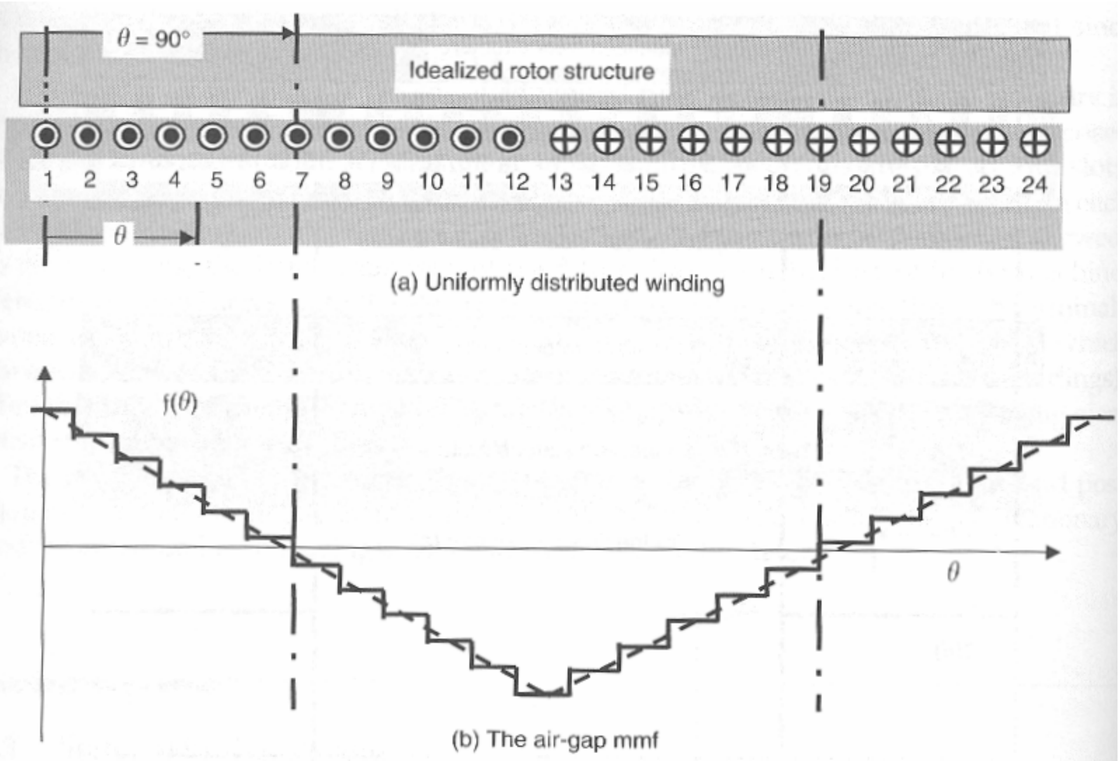
Indusert fasespenning i rotoren blir

$$E_{2f} = 4,44 \cdot f_2 \cdot N_2 \cdot \phi_{\text{max}} \tag{10.9}$$

hvor f_2 er rotorfrekvensen (lav frekvens ved normal drift) og N_2 er effektivt vindingstall per rotorfase. Siden vindingene ikke ligger over hverandre, vil de induserte spenningene være noe faseforskjøvet. Derfor vil effektivt vindingstall være noe lavere enn virkelig vindingstall.

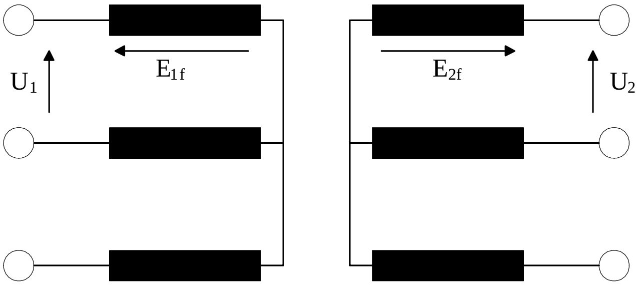
Hvis en låser fast rotor, vil stator- og rotorfrekvens være lik, og da kan formel (10.8) og (10.9) sammenfattes som

$$\frac{E_{1f}}{E_{2f}} = \frac{N_1}{N_2} \tag{10.10}$$



Figur 10.8: Fordelingen av amperevindinger (magnetomotorisk kraft - mmk) langs omkretsen av luftgapet

En maskin med fastlåst rotor vil altså fungere som en transformator. Dette gjelder kun for sleperingsmaskinen, hvor en kan ta ut rotorspenningene. Ved y-koblet stator vil kretsene da se ut som på figur 10.9.



Figur 10.9: Stator- og rotorkrets med y-koblet stator for stillestående maskin

Ser en bort fra spenningsfallene i viklingene (resistans og lekkreaktans), kan en ved stillestående rotor sette at

$$\frac{U_1}{U_2} = \frac{N_1}{N_2} \tag{10.11}$$

Et sentralt begrep knyttet til asynkronmaskinen, er sakkingen s. Når sakkingen er hundre prosent, skriver vi $s = 1,0$, og det betyr at motoren står stille. Når rotoren går synkront med dreiefeltet, sakker den ikke, og da setter vi $s = 0$. Skulle rotoren gå raskere enn feltet, blir sakkingen negativ. Blir rotoren presset til å gå baklengs, vil sakkingen være større enn 1 (mer enn 100 %). Forholdet mellom sakkingen s, luftgapsturtallet n_s (synkront turtall) og motorens turtall n (rotorturtallet) er gitt ved formel (10.12):

$$s = \frac{n_s - n}{n_s} \tag{10.12}$$

Når rotor får løpe fritt, vil rotor og stator ha ulik frekvens, og da gjelder ikke formlene (10.10) og (10.11) lenger. Forholdet mellom stator- og rotorfrekvensen er

$$f_2 = f_1 \cdot s \tag{10.13}$$

Rotorfrekvensen er altså proporsjonal med sakkingen. Ved stillstand vil den som før nevnt være lik statorfrekvensen. Ved synkron hastighet vil den være lik null.
Indusert rotorspenning vil ut fra formel (10.9) være proporsjonal med frekvensen, og dermed også med sakkingen:

$$E_{\text{2f,rotasjon}} = s \cdot E_{\text{2f,stillstand}} \tag{10.14}$$

Eksempel 2 *En 6-polig sleperingsmotor står tilkoblet* 400 *V* 50 *Hz. Ved åpen rotorkrets og stillestående rotor måles* 200 *V mellom to sleperinger.*

a)
Rotor drives i samme dreieretning som hovedfeltet ved hjelp av en annen motor mens rotorkretsen er åpen. Beregn rotorfrekvens og spenning mellom to sleperinger ved henholdsvis 200, 950 og 1200 o/min.
b)
Rotor drives med 200 o/min i motsatt dreieretning mens rotorkretsen fremdeles er åpen. Beregn rotorfrekvens og spenning mellom to sleperinger.

Løsning:
a)
Motorens synkrone turtall er

$$n_s = \frac{60 \cdot f}{p} = \frac{60 \cdot 50}{3} = 1000 \text{ o/min}$$

Sakking ved henholdsvis 200, 950 og 1200 o/min:

$$\begin{gathered} s_{200} = \tfrac{n_s - n}{n_s} = \tfrac{1000-200}{1000} = 0,80 \\ s_{950} = \tfrac{1000-950}{1000} = 0,050 \\ s_{1200} = \tfrac{1000-1200}{1000} = -0,20 \end{gathered}$$

Rotorfrekvensene blir:

$$\begin{gathered} f_{2,200} = s_{200} \cdot f_1 = 0,80 \cdot 50 = 40\,\text{Hz} \\ f_{2,950} = s_{950} \cdot f_1 = 0,050 \cdot 50 = 2,5\,\text{Hz} \\ f_{2,1200} = s_{1200} \cdot f_1 = |-0,20 \cdot 50| = 10\,\text{Hz} \end{gathered}$$

Spenningene mellom to sleperinger blir

$$U_{2,200} = s_{200} \cdot E_2 = 0,80 \cdot 200 = 160\,\mathrm{V}$$
$$U_{2,950} = s_{950} \cdot E_2 = 0,050 \cdot 200 = 10\,\mathrm{V}$$
$$U_{2,1200} = s_{1200} \cdot E_2 = |-0,20 \cdot 200| = 40\,\mathrm{V}$$

Det gir ingen mening å snakke om negativ frekvens eller vekselspenning. Derfor brukes absoluttverditegnet.

b)
Sakkingen blir

$$s_{-200} = \frac{n_s - n}{n_s} = \frac{1000 - (-200)}{1000} = 1,2$$

Frekvensen blir

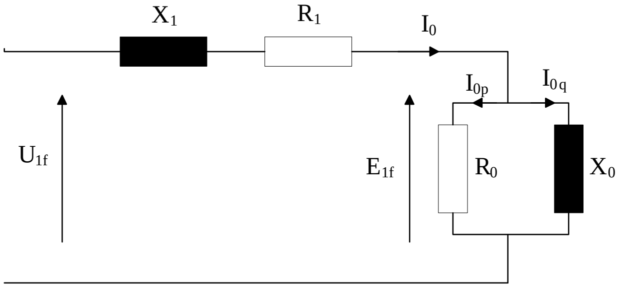
$$f_{2,-200} = s_{-200} \cdot f_1 = 1,2 \cdot 50 = 60\,\mathrm{Hz}$$

Spenningen mellom to sleperinger blir

$$U_{2,-200} = s_{-200} \cdot E_2 = 1,2 \cdot 200 = 240\,\mathrm{V}$$

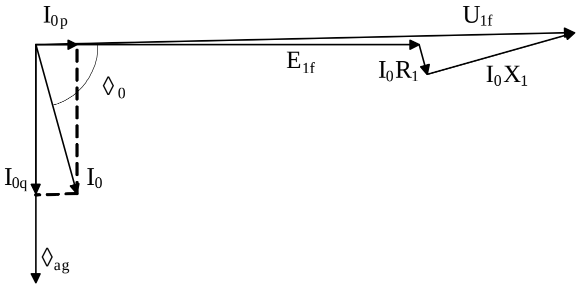
10.4 Ekvivalentskjema

For en sleperingsmaskin med åpen rotorkrets vil det ikke flyte strøm i rotorviklingene. Det samme gjelder hvis maskinen går med synkront turtall. Dette er en klar parallell til en transformator i tomgang, og ekvivalentskjemaet blir omtrent det samme. Dette er vist på figur 10.10. Tomgangsresistansen R_0 utgjøres av jerntap i den magnetiske massen. En kunne også innbefatte friksjonstap, men det er mer naturlig å regne dette som en del av den mekaniske lasten. Magnetiseringsreaktansen X_0 vil være betydelig lavere enn for en transformator, siden fluksen blir begrenset av et luftgap. Tomgangsstrømmen I_0 vil være så høy at en bør ta hensyn til spenningsfallet i statorviklingene og derfor inkludere viklingsresistansen R_1 og lekkreaktansen X_1 i tomgangsekvivalenten.



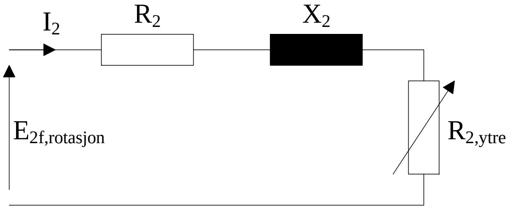
Figur 10.10: Ekvivalentskjema for asynkronmaskin i tomgang

Viserdiagrammet for denne ekvivalenten er vist på figur 10.11.



Figur 10.11: Viserdiagram for asynkronmaskin i tomgang

Ved belastning vil det gå en betydelig strøm i rotorkretsen. For en sleperingsmaskin vil rotorens faseekvivalent se ut som på figur 10.12. I tillegg til den indre resistansen R_2 i rotorviklingene og en ytre sleperingsmotstand $R_{2,ytre}$, vil rotoren ha en lekkreaktans X_2 som er proporsjonal med rotorfrekvensen, og dermed også med sakkingen. Påtrykt spenning i kretsen vil være den rotasjonsinduserte spenningen $E_{2f,rotasjon}$.



Figur 10.12: Faseekvivalent for rotor med ytre sleperingsmotstand

Hvis vi definerer E_{2f} og X_2 som henholdsvis indusert fasespenning og lekkreaktans i rotor ved stillstand, kan rotorstrømmen uttrykkes som

$$I_2 = \frac{s \cdot E_{2f}}{\sqrt{\left(R_2 + R_{2,ytre}\right)^2 + \left(sX_2\right)^2}} \tag{10.15}$$

Ved vanlig drift er rotoren kortsluttet, og da forenkles uttrykket i formel (10.15) til

$$I_2 = \frac{sE_{2f}}{\sqrt{\left(R_2\right)^2 + \left(sX_2\right)^2}} \tag{10.16}$$

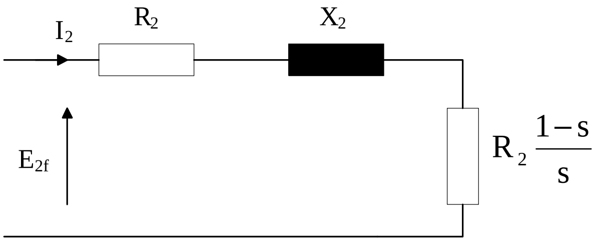
Dette uttrykket kan skrives om ved å dele på s både i teller og nevner:

$$I_2 = \frac{E_{2f}}{\sqrt{\left(\frac{R_2}{s}\right)^2 + \left(X_2\right)^2}} \tag{10.17}$$

Det er hensiktsmessig å dele uttrykket for resistansen i en konstant og en sakkingsavhengig del:

$$\frac{R_2}{s} = R_2 + R_2\frac{1-s}{s} \tag{10.18}$$

hvor det første leddet er et uttrykk for rotorresistansen og det andre leddet er et uttrykk for motorens mekaniske last omregnet til en elektrisk størrelse.

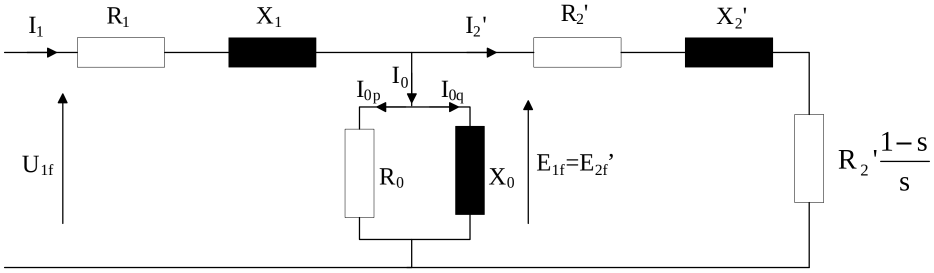


Figur 10.13: Faseekvivalent for kortsluttet rotor

Da vil rotorstrømmen være gitt ved

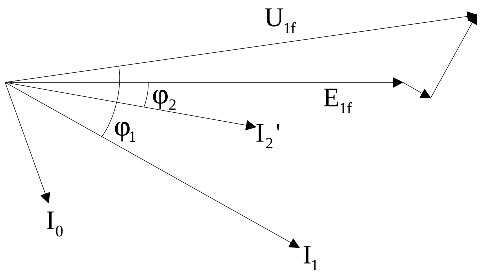
$$I_2 = \frac{E_{2f}}{\sqrt{\left(R_2 + R_2 \frac{1-s}{s}\right)^2 + X_2{}^2}} \tag{10.19}$$

Rotorkretsens faseekvivalent vil da se ut som på figur 10.13:
På samme måte som for transformatoren, kan man kombinere begge strømkretsene i en felles ekvivalent. Rotorkretsens komponenter må da regnes om med statorspenningen som referanse, og omregningen gjøres på samme måte. Det fullstendige ekvivalentskjemaet for asynkronmaskinen er vist på figur 10.14. Tilhørende viserdiagram er vist på figur 10.15.



Figur 10.14: Faseekvivalent for asynkronmaskin

Dersom maskinen går med oversynkront turtall, vil sakkingen bli negativ, og da vil den mekaniske resistansen helt til høyre i figuren også bli negativ. En negativ resistans er en spenningskilde, og det vil da flyte en strøm fra rotor og inn i stator. Ekvivalenten på figur 10.14 er med andre ord gyldig også i generatordrift.



Figur 10.15: Viserdiagram for asynkronmaskin

Eksempel 3 *En trefase asynkronmaskin er tilkoblet* $400\,\mathrm{V}$ $50\,\mathrm{Hz}$ *nett. Stator er y-koblet. Tabell 10.1 viser motorparameterne. Beregn linjestrømmene ved oppstart (stillstand) og ved en sakking på* 2% *(merketurtall).*

Tabell 10.1: Motorparametere

Parameter	Verdi
R_1	$1,5\,\Omega$
X_1	$2,5\,\Omega$
Z_0	$40\,\Omega\angle 45\,^\circ$
$R_2\,'$	$3,0\,\Omega$
$X_2\,'$	$5,0\,\Omega$

Løsning:
Y-koblet stator gir fasespenning $U_{1f} = 230\,\mathrm{V}$
Kretsens totale impedans er gitt ved:

$$\overrightarrow{Z}_{tot} = R_1 + jX_1 + \overrightarrow{Z}_0 || \left(\frac{R_2\,'}{s} + jX_2\,' \right)$$

Ved stillstand er sakkingen $s = 1,0$. Da blir rotorimpedansen

$$\overrightarrow{Z}_2\,' = R_2\,' + jX_2\,' = (3,0 + j5,0)\ \Omega$$

Total impedans er

$$\overrightarrow{Z}_{start} = (1,5 + j2,5)\ \Omega + \frac{(3,0 + j5,0)\ \Omega \cdot (40\,\Omega\angle 45\,^\circ)}{(3,0 + j5,0)\ \Omega + (40\,\Omega\angle 45\,^\circ)} = 8,0\,\Omega\angle 57,9\,^\circ$$

Startstrømmen blir da

$$I_{start} = \frac{U_{1f}}{Z_{start}} = \frac{230}{8,0} = 28,8\,\mathrm{A}$$

Ved merketurtall blir rotorimpedansen

$$\overrightarrow{Z}_2\,' = \frac{R_2\,'}{s} + jX_2\,' = \left(\frac{3,0}{0,02} + j5,0 \right)\ \Omega = (150 + j5,0)\ \Omega$$

Total impedans er

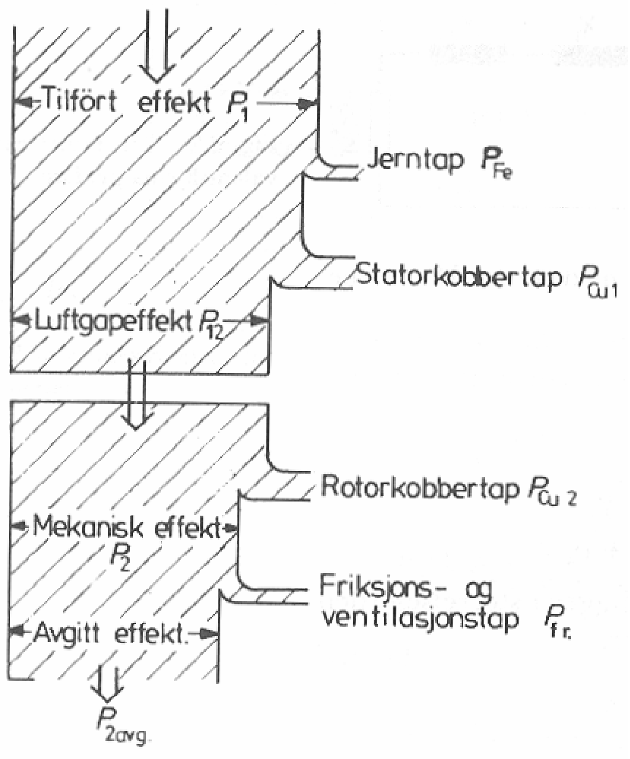
$$\overrightarrow{Z}_N = (1,5 + j2,5)\ \Omega + \frac{(150 + j5,0)\ \Omega \cdot (40\,\Omega\angle 45\,^\circ)}{(150 + j5,0)\ \Omega + (40\,\Omega\angle 45\,^\circ)} = 35,8\,\Omega\angle 38,1\,^\circ$$

Merkestrømmen er

$$I_N = \frac{U_{1f}}{Z_N} = \frac{230}{35,8} = 6,42\,\mathrm{A}$$

10.5 Moment og turtall

En asynkronmotor får tilført en aktiv elektrisk effekt P_1 over statorklemmene. Dette er vist på figur 10.16. Noe av denne effekten går tapt i jernet og i viklingene. Hoveddelen av effekten vil likevel overføres via luftgapet til rotor. Det vil være noen kobbertap og friksjonstap i rotor, og resten av effekten tas ut på motorakselen som avgitt mekanisk effekt.



Figur 10.16: Flyt av aktiv effekt gjennom asynkronmotor

Luftgapseffekten vil være gitt ved tilført effekt minus statortapene (jerntap og strømvarmetap):

$$P_{12} = P_1 - \left(P_{Fe} + 3R_1{I_1}^2\right) \tag{10.20}$$

Den mekaniske effekten (inkludert friksjon) vil bestå av luftgapseffekten minus rotorens strømvarmetap:

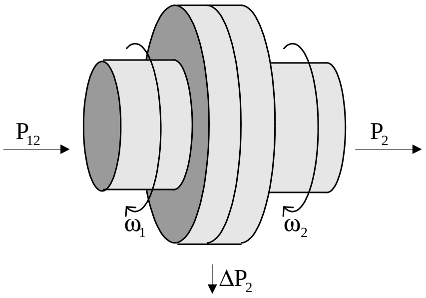
$$P_2 = P_{12} - 3\left(R_2 + R_{2,ytre}\right){I_2}^2 - P_{Fr} \tag{10.21}$$

Effektene i en roterende elektrisk maskin kan også uttrykkes ved moment og vinkelhastighet:

$$\begin{aligned} P_{12} &= \omega_1 T_{el} = \tfrac{2\pi n_s}{60} \cdot T_{el} \\ P_2 &= \omega_2 T_{el} = \tfrac{2\pi n}{60} \cdot T_{el} \end{aligned} \tag{10.22}$$

hvor T_{el} er motorens drivmoment.

Momentet vil være det samme på begge sider av luftgapet, men turtallet er forskjellig. Dette kan sammenlignes med en slurekobling (figur 10.17) hvor det samme vil være tilfelle: I en slik slurekobling vil en del av effekten gå tapt i friksjonsvarme. I asynkronmaskinen forsvinner noe av effekten som strømvarmetap i rotor.



Figur 10.17: Mekanisk analogi til asynkronmaskinens effektoverføring

Rotortapet ΔP_2 kan uttrykkes ved

$$\Delta P_2 = P_{12} - P_2 = 3\left(R_2 + R_{2,ytre}\right) I_2{}^2 \tag{10.23}$$

Kombinert med formel (10.22), gir dette at

$$\Delta P_2 = \left(\omega_1 - \omega_2\right) T = \frac{\omega_1 - \omega_2}{\omega_1}\omega_1 T = \frac{n_s - n}{n_s}\omega_1 T \tag{10.24}$$

som kan forenkles til

$$\Delta P_2 = s \cdot P_{12} \tag{10.25}$$

Rotortapet er altså proporsjonalt med sakkingen.
Det elektrodynamiske drivmomentet kan skrives som

$$\begin{aligned} T_{el} &= \frac{P_{12}}{\omega_1} = \frac{P_2}{\omega_2} = \frac{\Delta P_2}{\omega_1 - \omega_2} = \frac{\Delta P_2}{\omega_1 - \omega_2}\frac{\omega_1}{\omega_1} = \frac{\Delta P_2}{\omega_1}\frac{\omega_1}{\omega_1 - \omega_2} \\ &= \frac{\Delta P_2}{\omega_1}\frac{n_s}{n_s - n} = \frac{\Delta P_2}{\omega_1}\frac{1}{s} = \frac{3\left(R_2 + R_{2,ytre}\right) I_2{}^2}{\omega_1 s} \end{aligned} \tag{10.26}$$

Kvadratet av rotorstrømmen kan skrives som

$$I_2{}^2 = \frac{\left(s \cdot E_{2f}\right)^2}{\left(R_2 + R_{2,ytre}\right)^2 + \left(s \cdot X_2\right)^2} \tag{10.27}$$

Setter vi (10.27) inn i (10.26), kan momentet skrives som

$$T_{el} = \frac{3\left(R_2 + R_{2,ytre}\right)\left(s \cdot E_{2f}\right)^2}{\omega_1 s\left[\left(R_2 + R_{2,ytre}\right)^2 + \left(s \cdot X_2\right)^2\right]} \tag{10.28}$$

Siden sakkingen s er den eneste variable størrelsen, gir (10.28) dreiemomentet som funksjon av sakkingen.
For å finne det maksimale drivmomentet (kippmomentet), deriverer en (10.28) med hensyn på sakkingen og setter den deriverte lik null. En finner da den sakkingen som gir maksimalt drivmoment. Denne sakkingen kalles kippsakkingen s_m og er gitt ved

$$s = s_m = \frac{R_2 + R_{2,ytre}}{X_2} \text{ for } \frac{dT}{ds} = 0 \tag{10.29}$$

Hvis en setter denne verdien inn i (10.28), finner en kippmomentet T_{max}:

$$T_{\max} = \frac{3{E_{2f}}^2}{2\omega_1 X_2} = k_1 {E_{2f}}^2 \tag{10.30}$$

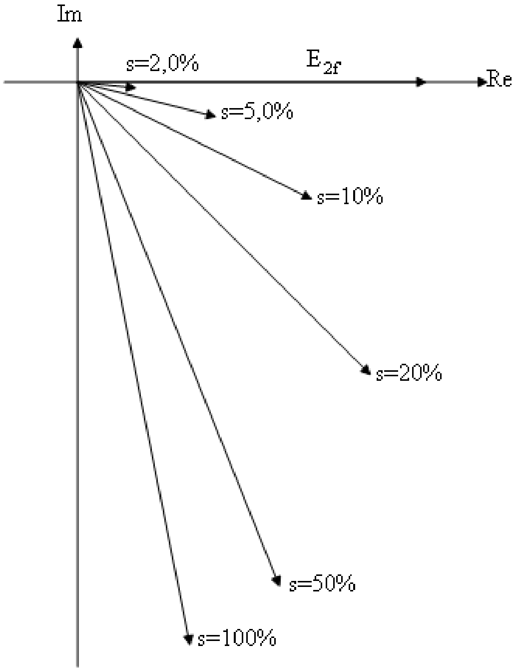
En ser at kippmomentet er proporsjonalt med kvadratet av indusert statorspenning. Dermed må det også være proporsjonalt med kvadratet av påtrykt spenning:

$$T_{\max} = k_2 {U_1}^2 \tag{10.31}$$

Hvis en setter formel (10.29) og (10.30) inn i (10.28), kan en skrive dreiemomentet som funksjon av sakkingen:

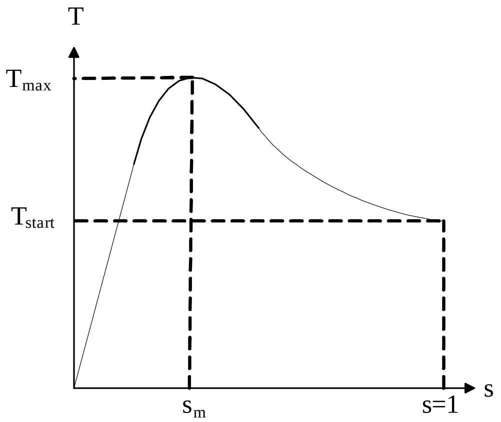
$$T_{el} = T_{\max} \frac{2 \cdot s \cdot s_m}{s^2 + {s_m}^2} \tag{10.32}$$

En ser av figur 10.18 at rotorstrømmen blir mer og mer induktiv ved økende sakking. Den vil først øke tilnærmet lineært og etter hvert flate ut, siden både indusert spenning og lekkreaktans i rotor øker proporsjonalt med sakkingen. Det er bare den aktive komponenten av rotorstrømmen som utvikler drivmoment, og derfor vil momentet være høyest når rotorresistansen og lekkreaktansen er like store.



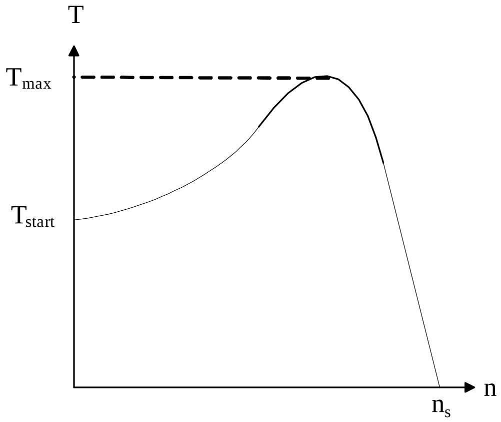
Figur 10.18: Rotorstrømmen ved ulik sakking med indusert rotorspenning som referanse

Figur 10.19 viser drivmomentet som en funksjon av sakkingen i området fra synkront turtall til stilllstand.



Figur 10.19: Dreiemoment som funksjon av sakkingen ved konstant rotorresistans

Det vil være mer interessant å vise drivmomentet som en funksjon av turtallet enn av sakkingen. Siden turtallet er høyt når sakkingen er lav, og omvendt, speilvender en ganske enkelt grafen på figur 10.19 for å få frem en slik karakteristikk:



Figur 10.20: Dreiemoment som funksjon av turtallet ved konstant rotorresistans

Eksempel 4 *En* 4*-polig trefase asynkronmotor står tilkoblet et* 50 *Hz nett og avgir* $3,0$ *kW på akselen ved* 1455 *o/min. Ved nedbremsing til kippmomentet blir turtallet* 1200 *o/min. Beregn rotorfrekvensen ved* 1455 *o/min, luftgapseffekt og rotortap ved* 1455 *o/min, dreiemoment ved* 1455 *o/min, kippmomentet og startmomentet.*

Løsning:
Synkront turtall er

$$n_s = \frac{60 \cdot f_1}{p} = \frac{60 \cdot 50}{2} = 1500 \text{ o/min}$$

Sakkingen ved 1455 o/min er

$$s = \frac{n_s - n}{n_s} = \frac{1500 - 1455}{1500} = 0,030$$

Rotorfrekvensen ved 1455 o/min er

$$f_2 = s \cdot f_1 = 0,030 \cdot 50 = 1,5\,\mathrm{Hz}$$

Rotortapet er gitt ved

$$\Delta P_2 = s \cdot P_{12} = P_{12} - P_2$$

Vi løser ligningen med hensyn på P_{12} som er den eneste ukjente:

$$\begin{aligned}
s \cdot P_{12} &= P_{12} - P_2 \\
s \cdot P_{12} - P_{12} &= -P_2 \\
P_{12} - s \cdot P_{12} &= P_2 \\
P_{12}\,(1 - s) &= P_2 \\
P_{12} &= \frac{P_2}{1 - s} = \frac{3000}{1 - 0,030} = 3093\,\mathrm{W}
\end{aligned}$$

Rotortapet blir

$$\Delta P_2 = s \cdot P_{12} = 0,030 \cdot 3093 = 93\,\mathrm{W}$$

Vinkelhastigheten ved 1455 o/min er

$$\omega_2 = \frac{2\pi n}{60} = \frac{2\pi \cdot 1455}{60} = 152\,\mathrm{rad/\,s}$$

Dreiemomentet ved 1455 o/min er

$$T = \frac{P_2}{\omega_2} = \frac{3000}{152} = 19,7\,\mathrm{N\,m}$$

Kippsakkingen er

$$s_m = \frac{n_s - n_m}{n_s} = \frac{1500 - 1200}{1500} = 0,20$$

Formelen for dreiemoment er gitt ved (10.32):

$$T = T_{\max} \frac{2 \cdot s \cdot s_m}{s^2 + s_m^2}$$

Vi løser denne med hensyn på kippmomentet:

$$\begin{aligned}
T &= T_{\max} \frac{2 \cdot s \cdot s_m}{s^2 + s_m^2} \\
T_{\max} &= T \frac{s^2 + s_m^2}{2 \cdot s \cdot s_m} = 19,7 \cdot \frac{0,030^2 + 0,20^2}{2 \cdot 0,030 \cdot 0,20} = 67,2\,\mathrm{N\,m}
\end{aligned}$$

For å finne startmomentet brukes formel (10.32) med $s = 1,0$ (stillstand):

$$T_{start} = T_{\max} \frac{2 \cdot s \cdot s_m}{s^2 + s_m^2} = 67,2 \cdot \frac{2 \cdot 1,0 \cdot 0,20}{1,0^2 + 0,20^2} = 25,8\,\mathrm{N\,m}$$

10.6 Tap og virkningsgrad

I likhet med en transformator skiller en mellom belastningsuavhengige tap (tomgangstap) og belastningstap.Tomgangstapene består av jerntap (hysterese og virvelstrømmer) og friksjonstap (lagerfriksjon, eventuell børstefriksjon, luftmotstand i vifter og andre deler).

$$P_0 = P_{Fe} + P_{fr} \tag{10.33}$$

Belastningstapene er rene strømvarmetap i statorviklingene, i rotorviklingene og i eventuelle børster. I likhet med transformatoren vil også vekselstrømsmaskinen ha tilleggstap som skyldes strømfortrengning og virvelstrømmer i nærliggende metalldeler.

$$P_b = 3\left(R_1 {I_1}^2 + R_2 {I_2}^2\right) + P_{\text{børste}} + P_{till} \tag{10.34}$$

De samlede tapene blir

$$\Delta P = P_0 + P_b \tag{10.35}$$

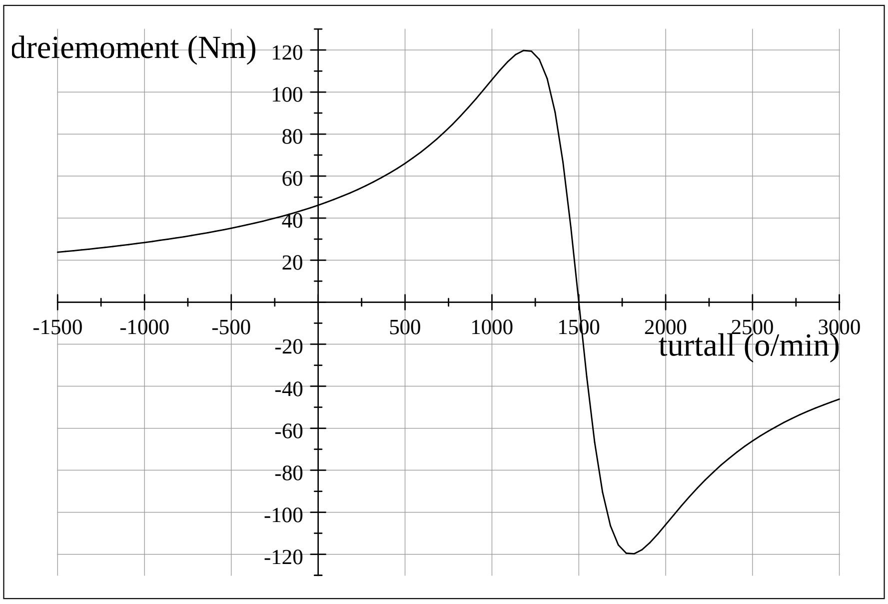
Virkningsgraden er definert som

$$\eta = \frac{P_2}{P_1} = \frac{P_2}{P_2 + \Delta P} = \frac{P_1 - \Delta P}{P_1} \tag{10.36}$$

og ligger typisk lavere enn 80 % for små maskiner (under 1 kW). For store maskiner (over 1 MW) kan virkningsgraden overstige 95 %.

10.7 Driftsformer

Figur 10.21 viser en moment/turtallskarakteristikk for en 4-polig maskin, og da er synkront turtall $n_s = 1500$ o/min.



Figur 10.21: Moment/turtallskarakteristikk for 4-polig asynkronmaskin

I området fra null til 1500 o/min går maskinen som motor. Dersom en ytre mekanisk kraftkilde (en turbin eller en drivmotor) driver turtallet over 1500 o/min, blir dreiemomentet negativt (maskinen utvikler et bremsemoment) og maskinen går som generator. Den vil da ta opp mekanisk effekt på akselen og levere aktiv effekt til nettet.

Dersom maskinen tvinges til å gå baklengs (rotor går i motsatt retning av dreiefeltet), går maskinen i bremsedrift. Den mekaniske effekten som blir tatt opp på akselen, vil da bli omsatt til strømvarmetap i rotoren.

Motordrift er den mest vanlige driftsformen for en asynkronmaskin. Den vil normalt gå med en sakking på $2 - 4$ %. Under varierende lastforhold (f. eks. en heisdrift), kan maskinen i korte perioder gå som generator fordi den mekaniske lasten driver maskinen opp i oversynkront turtall. Dette kalles regenerativ bremsing, og maskinen leverer effekt til nettet.

Generatordrift er mest vanlig ved vindturbiner. Da vil vindturbinen drive maskinen rundt slik at den går med oversynkront turtall. Skulle vinden stanse, vil maskinen drive vindturbinen rundt og dermed begynne å gå i motordrift. Ved generatordrift går maskinen oversynkront. Som det fremgår av figur 10.21, blir momentet negativt, idet drivmomentet går over til å bli et bremsemoment. Rotorstrømmen endrer retning, og resultatet er at maskinen omdanner tilført mekanisk effekt til avgitt elektrisk effekt. Det må imidlertid tilføyes at maskinen er avhengig av å være tilkoblet et spenningssatt nett for å magnetiseres, og den vil alltid trekke reaktiv effekt, også i generatordrift.

Hvis man ønsker å stanse en motor raskt, snur man retningen på dreiefeltet mens motoren er i gang. Den vil da gå over i bremsedrift. På grunn av de økte rotortapene, bør ikke denne oppbremsingen vare lenge eller gjentas for ofte. Det kan nemlig medføre varmgang.

10.8 Motorstyring

Turtallet til en asynkronmaskin er gitt ved

$$n = (1 - s)\, n_s = (1 - s)\, \frac{60 \cdot f_1}{p} \tag{10.37}$$

Formel (10.37) viser at det er tre størrelser som påvirker turtallet: sakkingen s, statorfrekvensen f_1 og polpartallet p.

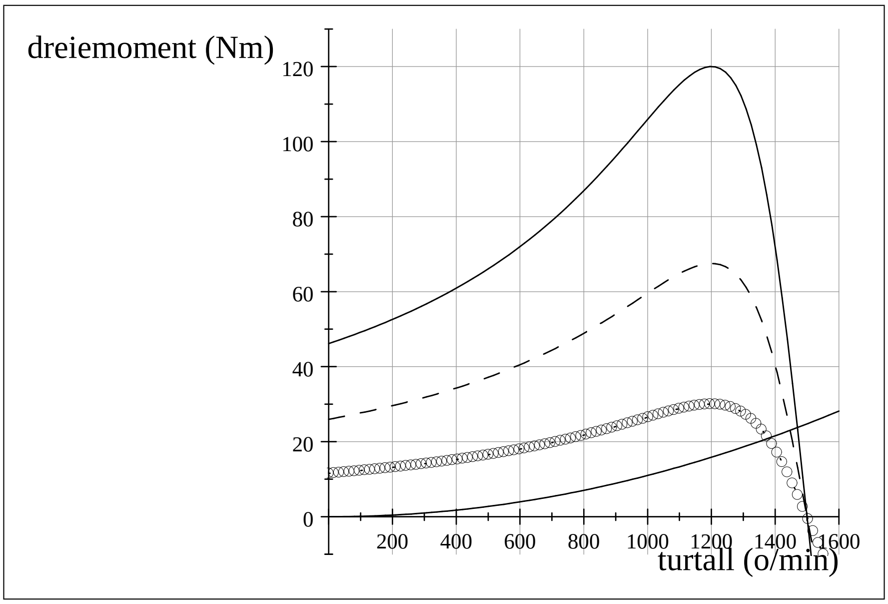
Sakkingsregulering

Endring av sakkingen kan gjøres enten ved å endre påtrykt spenning U_1 eller ved å endre kippsakkingen s_m. Formel (10.31) viser at kippmomentet endrer seg med kvadratet av klemmespenningen:

$$\mathrm{T}_{\mathrm{max}} = \mathrm{k}_2 \mathrm{U}_1^2 \tag{10.38}$$

Dette innebærer at en halvering av klemmespenningen reduserer kippmomentet til en firedel av opprinnelig verdi.

Figur 10.22 viser moment/turtallskarakteristikker for ulike klemmespenninger (heltrukket linje er full spenning, stiplet linje er 75% spenning, og linje markert med sirkler er 50% spenning). En ser av figuren at momentet endrer seg svært ulineært, og at arbeidspunktet (skjæringen mellom driv- og lastmoment) flytter seg lite. Spenningsregulering gir et smalt arbeidsområde, og metoden er risikabel. Har man senket klemmespenningen og det i tillegg inntreffer et spenningsfall på nettet, kan man risikere at motoren stanser fordi drivmomentet blir lavere enn lastmomentet.



Figur 10.22: Hastighetsregulering av asynkronmaskin med spenningsregulering

Eksempel 5 *En* $5,0\,\mathrm{kW}$ *asynkronmaskin med tre polpar står tilkoblet et* $230\,\mathrm{V}$ $50\,\mathrm{Hz}$ *nett. Merketurtallet er* 970 *o/min, og maskinen har en kippsakking på* 20%*. Lasten har et konstant moment på* $50\,\mathrm{N\,m}$*. Beregn kippmomentet og startmomentet ved merkespenning. Hva hender med kippmomentet og startmomentet hvis spenningen reduseres til* $205\,\mathrm{V}$ *eller* $175\,\mathrm{V}$*?*

Løsning:

Synkront turtall er

$$n_s = \frac{60 \cdot f_1}{p} = \frac{60 \cdot 50}{3} = 1000 \text{ o/min}$$

Merkesakkingen er

$$s_N = \frac{n_s - n_N}{n_s} = \frac{1000 - 970}{1000} = 3,0\%$$

Vinkelhastigheten ved merkedrift er

$$\omega_N = \frac{n_N}{9,55} = \frac{970}{9,55} = 101\,\mathrm{rad/\,s}$$

Det gir følgende merkemoment:

$$T_N = \frac{P_N}{\omega_N} = \frac{5000}{101} \approx 50\,\mathrm{N\,m}$$

Kippmomentet er

$$T_{\max} = T_N \frac{{s_N}^2 + {s_m}^2}{2 \cdot s_N \cdot s_m} = 50 \cdot \frac{0,03^2 + 0,2^2}{2 \cdot 0,03 \cdot 0,2} = 170\,\mathrm{N\,m}$$

Startmomentet er

$$T_{start} = T_{\max} \cdot \frac{2 \cdot s \cdot s_m}{s^2 + {s_m}^2} = 170 \cdot \frac{2 \cdot 1 \cdot 0,2}{1^2 + 0,2^2} = 65\,\mathrm{N\,m}$$

Ved $205\,\mathrm{V}$ blir kippmomentet

$$T_{\max,205} = T_{\max,230} \left(\frac{205}{230}\right)^2 = 170 \cdot \left(\frac{205}{230}\right)^2 = 135\,\mathrm{N\,m}$$

Startmomentet blir

$$T_{start,205} = T_{start,230} \left(\frac{205}{230}\right)^2 = 65 \cdot \left(\frac{205}{230}\right)^2 = 52\,\mathrm{N\,m}$$

Ved $175\,\mathrm{V}$ blir kippmomentet

$$T_{\max,175} = T_{\max,230} \left(\frac{175}{230}\right)^2 = 170 \cdot \left(\frac{175}{230}\right)^2 = 98\,\mathrm{N\,m}$$

Startmomentet blir

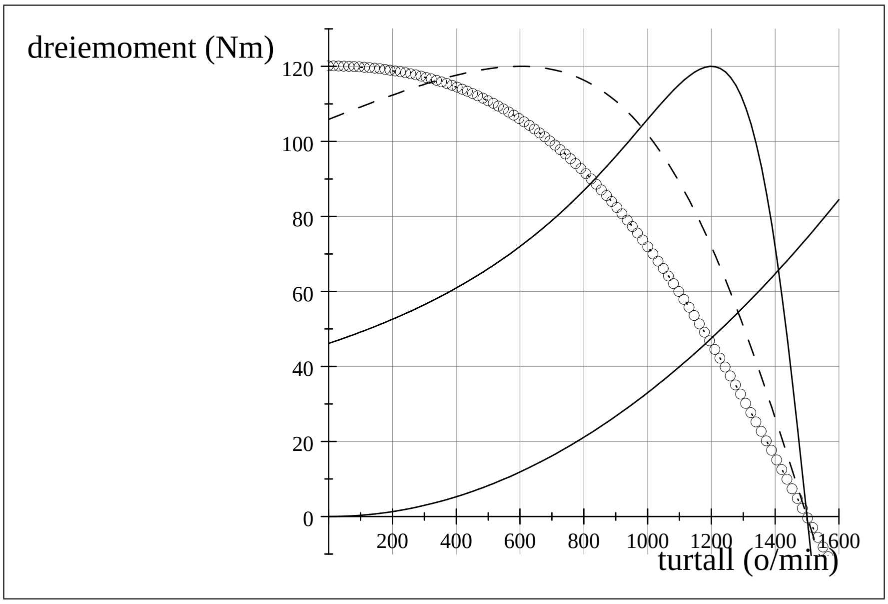
$$T_{start,175} = T_{start,230} \left(\frac{175}{230}\right)^2 = 65 \cdot \left(\frac{175}{230}\right)^2 = 38\,\mathrm{N\,m}$$

Vi ser at maskinen vil klare å ta en svært langsom oppstart ved en spenning på $205\,\mathrm{V}$, mens den ikke vil greie å starte ved en spenning på $175\,\mathrm{V}$.

Formel (10.29) viser at kippsakkingen kan endres ved hjelp av en ytre rotorresistans:

$$s_m = \frac{R_2 + R_{2,\text{ytre}}}{X_2} \tag{10.39}$$

Figur 10.23 viser moment/turtallskarakteristikker for ulike verdier av den ytre rotorresistansen (Heltrukket linje: $R_{2,ytre} = 0$, stiplet linje: $R_{2,ytre} = 2R_2$, sirkelmerket linje: $R_{2,ytre} = 4R_2$). En ser at reguleringsområdet blir mye større. Dessuten vil kippmomentet være like høyt for alle kurver. En kan derfor øke startmomentet. Ulempen er effekttapet i rotorresistansen, samt at metoden bare kan brukes på sleperingsmaskiner.



Figur 10.23: Hastighetsregulering av sleperingsmaskin med ytre rotorresistans

Eksempel 6 *En sekspolig sleperingsmaskin er tilkoblet et trefase* $50\,\mathrm{Hz}$ *nett. Maskinen har et merketurtall* $n_N = 950$ *o/min ved en merkeeffekt* $P_{2N} = 2,0\,\mathrm{kW}$*. Den indre rotorresistansen* $R_2 = 0,2\,\Omega$ *og lekkreaktansen* $X_2 = 1,0\,\Omega$*. Beregn kippsakking, kippmoment og startmoment.*
En ytre sleperingsresistans kobles til. Beregn kippsakking og startmoment ved a) $R_{2,ytre} = 0,3\,\Omega$*, b)* $R_{2,ytre} = 0,6\,\Omega$*, c)* $R_{2,ytre} = 0,8\,\Omega$*.*

Løsning:
Synkront turtall:

$$n_s = \frac{60f_1}{p} = \frac{60 \cdot 50}{3} = 1000 \text{ o/min}$$

Merkesakking:

$$s_N = \frac{n_s - n_N}{n_s} = \frac{1000 - 950}{1000} = 5,0\%$$

Vinkelhastighet ved merkedrift:

$$\omega_{2N} = \frac{2\pi}{60} n_N = \frac{2\pi}{60} 950 = 99,5\,\mathrm{rad/\,s}$$

Merkemoment:

$$T_N = \frac{P_{2N}}{\omega_{2N}} = \frac{2000}{99,5} = 20,1\,\mathrm{N\,m}$$

Kippsakking:

$$s_m = \frac{R_2}{X_2} = \frac{0,2}{1,0} = 20\%$$

Kippmoment:

$$T_{\max} = T_N \frac{{s_N}^2 + {s_m}^2}{2 \cdot s_N \cdot s_m} = 20,1 \cdot \frac{0,05^2 + 0,2^2}{2 \cdot 0,05 \cdot 0,2} = 42,7\,\mathrm{N\,m}$$

Startmoment:

$$T_{start} = T_{\max} \cdot \frac{2 \cdot s \cdot s_m}{s^2 + {s_m}^2} = 42,7 \cdot \frac{2 \cdot 1 \cdot 0,2}{1^2 + 0,2^2} = 16,4\,\mathrm{N\,m}$$

a)
Kippsakking:

$$s_m = \frac{R_2 + R_{2,ytre}}{X_2} = \frac{0,2 + 0,3}{1,0} = 50\%$$

Startmoment:

$$T_{start} = 42,7 \cdot \frac{2 \cdot 1 \cdot 0,5}{1^2 + 0,5^2} = 34,1\,\mathrm{N\,m}$$

b)
Kippsakking:

$$s_m = \frac{R_2 + R_{2,ytre}}{X_2} = \frac{0,2 + 0,6}{1,0} = 80\%$$

Startmoment:

$$T_{start} = 42,7 \cdot \frac{2 \cdot 1 \cdot 0,8}{1^2 + 0,8^2} = 41,7\,\mathrm{N\,m}$$

c)
Kippsakking:

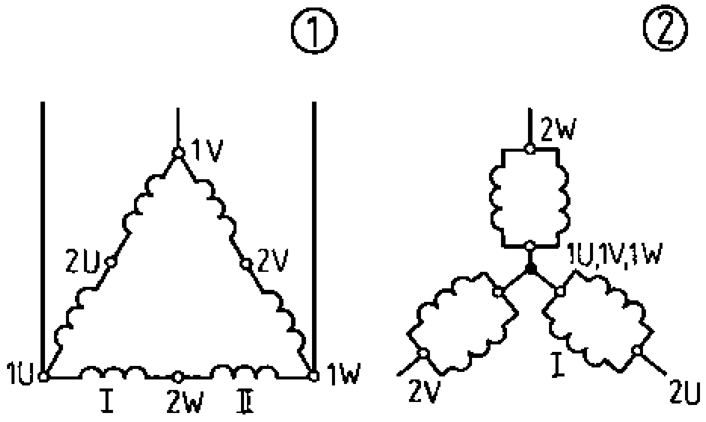
$$s_m = \frac{R_2 + R_{2,ytre}}{X_2} = \frac{0,2 + 0,8}{1,0} = 100\%$$

Startmoment:

$$T_{start} = 42,7 \cdot \frac{2 \cdot 1 \cdot 1,0}{1^2 + 1,0^2} = 42,7\,\mathrm{N\,m}$$

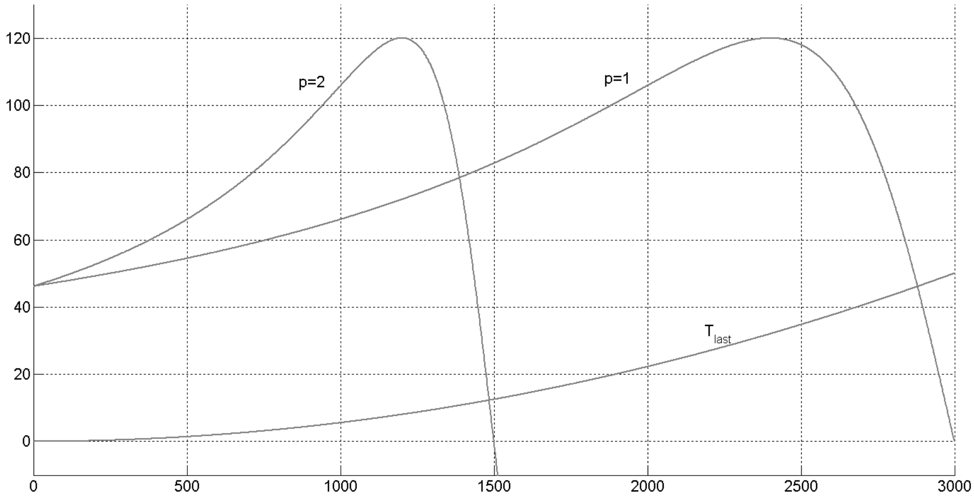
Dahlanderkobling

Som det fremgår av (10.37), kan en endre turtallet ved å endre antall polpar i statorfeltet. En bruker da en burviklet maskin med såkalt Dahlanderkobling, eller flere sett med statorspoler. Prinsippet for Dahlanderkoblingen er vist på figur 10.24.



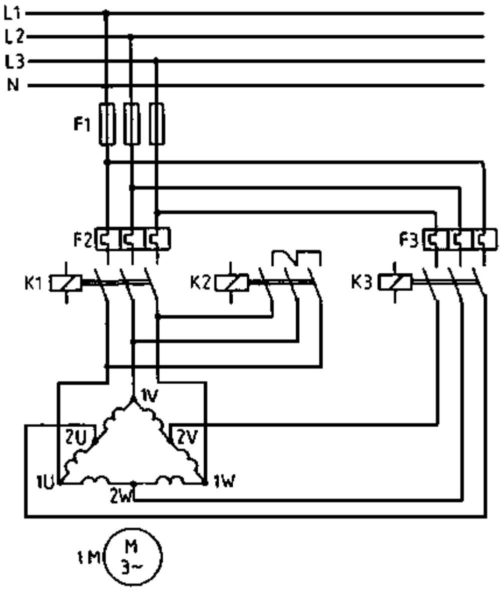
Figur 10.24: Prinsipp for Dahlanderkobling

Hver fase har to statorviklinger. Ved lav hastighet (1) er de koblet i serie, slik at det oppstår to polpar, og synkront turtall er 1500 o/min. Ved høy hastighet (2) kobles de i parallell, og det oppstår ett polpar i dreiefeltet. Synkront turtall blir da 3000 o/min. Dette fremgår av figur 10.25.



Figur 10.25: Hastighetsregulering av asynkronmaskin med Dahlanderkobling

Figur 10.26 viser koblingsskjema for en Dahlanderkobling. Ved lav hastighet ligger K1 inne. Ved høy hastighet ligger K2 og K3 inne.

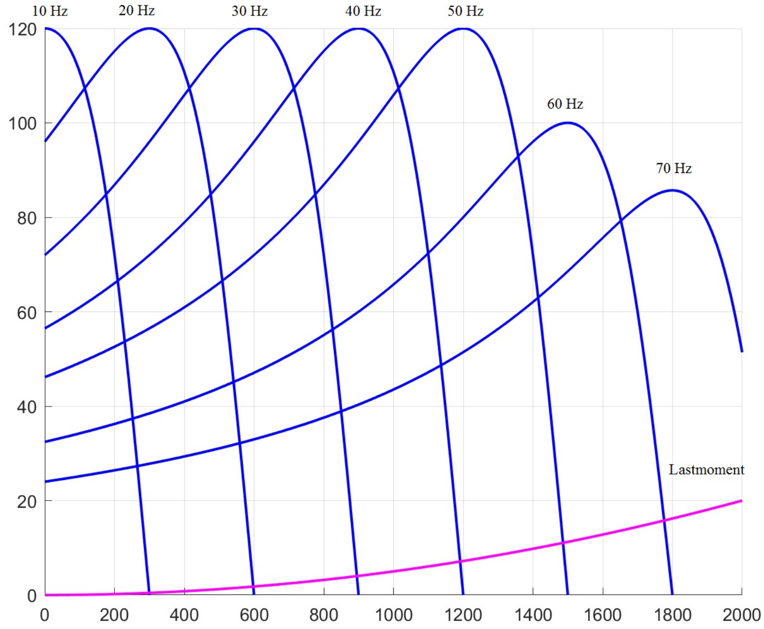


Figur 10.26: Koblingsskjema for Dahlanderkobling

Endring av polpartallet brukes i dag mest til vindturbiner. Det er vanlig å veksle mellom firepolte og sekspolte statorviklinger, og slik kan man flytte synkront turtall fra 1500 o/min til 1000 o/min og på denne måten utnytte et bredere spekter av vindhastigheter. Metoden krever at maskinen er utstyrt med to sett statorviklinger og brukes bare på maskiner med burviklede rotorer.

Frekvensregulering

En mye mer elegant måte å regulere turtallet på, er gjennom å regulere statorfrekvensen f_1. Dette er vist på figur 10.27. Med denne metoden kan man flytte arbeidspunktet hvor man vil, og man kan sågar bruke en statorfrekvens høyere enn 50 Hz og dermed oppnå et turtall over 1500 o/min, hvis maskinen er bygd for det.



Figur 10.27: Hastighetsregulering av asynkronmaskin med frekvensregulering

Hittil er sakkingen blitt definert i forhold til synkront turtall, med andre ord en relativ sakking:

$$s = \frac{n_s - n}{n_s} \tag{10.40}$$

Ved frekvensstyring må man også se på turtallsforskjellen mellom statorfeltet og rotor (absolutt sakking), for det er denne turtallsforskjellen som skaper moment:

$$T = k\,(n_s - n) = k \cdot \Delta n \tag{10.41}$$

Formel (10.40) gir bare mening ved merkefrekvens. Ved andre statorfrekvenser må en benytte den absolutte sakkingen Δn i utregningene. Da kan synkront turtall bestemmes ut fra rotorturtall og sakking:

$$n_s = n + \Delta n$$

Formel (10.1) løses så med hensyn på statorfrekvensen:

$$f_1 = \frac{n_s \cdot p}{60}$$

Formel (10.8) angir forholdet mellom indusert spenning, frekvens og fluks i statorkretsen:

$$\mathrm{E}_{1\mathrm{f}} = 4{,}44 \cdot \mathrm{f}_1 \cdot \mathrm{N}_1 \cdot \phi_{\max} \tag{10.42}$$

Dersom en ønsker å holde fluksen, og dermed også kippmomentet konstant, vil påtrykt spenning og statorfrekvens være proporsjonale:

$$U_1 = k \cdot f_1 \tag{10.43}$$

Klemmespenningen må imidlertid ikke overskride maskinens merkespenning. Ved frekvenser over 50Hz holdes spenningen konstant, og fluksen svekkes:

$$\phi_{\max} = k\frac{U_{1N}}{f_1} \tag{10.44}$$

Når feltet svekkes, vil også momentet svekkes, og dette vises tydelig til høyre på figur 10.27.

Eksempel 7 *Maskinen i eksempel 5 tilkobles en frekvensstyring. Lasten er fortsatt konstant* $T_{last} = 50\,\mathrm{N\,m}$. *Vi ønsker å endre turtallet til* 500 *o/min. Hva blir statorfrekvensen og -spenningen? Hva blir kippmomentet ved en frekvens på* $75\,\mathrm{Hz}$*?*

Løsning:
Absolutt sakking ved merkemoment er

$$\Delta n = n_s - n_N = 1000 - 970 = 30 \text{ o/min}$$

Ved et rotorturtall $n = 500$ o/min, blir synkront turtall:

$$n_s = n + \Delta n = 500 + 30 = 530 \text{ o/min}$$

Det gir følgende statorfrekvens:

$$f_1 = \frac{n_s \cdot p}{60} = \frac{530 \cdot 3}{60} = 26,5\,\mathrm{Hz}$$

Statorspenningen er

$$U_1 = U_{1N}\frac{f_1}{f_{1N}} = 230 \cdot \frac{26,5}{50} = 122\,\mathrm{V}$$

Formel (10.44) angir at fluksen, og dermed også kippmomentet er omvendt proporsjonalt med feltet ved statorfrekvenser over $50\,\mathrm{Hz}$. Kippmomentet ved $75\,\mathrm{Hz}$ blir dermed

$$T_{\max,75} = T_{\max,50}\frac{50}{75} = 170 \cdot \frac{50}{75} = 113\,\mathrm{N\,m}$$

Eksempel 8 *Lasten i eksempel 7 byttes ut med ei pumpe som utvikler* $50\,\mathrm{N\,m}$ *ved et turtall på* 970 *o/min. Hva blir statorspenningen og -frekvensen ved et turtall på* 500 *o/min?*

Løsning
Siden lasten er ei pumpe, har den kvadratisk karakteristikk:

$$T_{last} = k \cdot n^2$$

Lastmomentet ved 500 o/min blir dermed

$$T_{last} = 50 \cdot \left(\frac{500}{970}\right)^2 = 13,3\,\mathrm{N\,m}$$

Siden vi antar at det er en lineær sammenheng mellom moment og absolutt sakking, vil denne bli

$$\Delta n = 30 \cdot \frac{13,3}{50} = 8,0 \text{ o/min}$$

Synkront turtall blir da

$$n_s = n + \Delta n = 500 + 8,0 = 508 \text{ o/min}$$

Statorfrekvensen blir

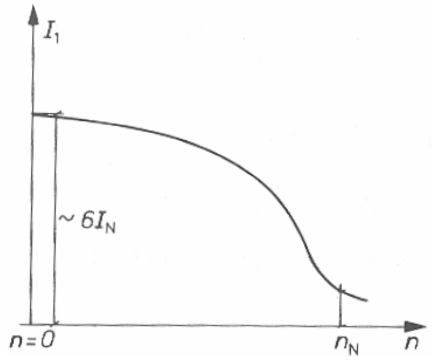
$$f_1 = \frac{n_s \cdot p}{60} = \frac{508 \cdot 3}{60} = 25,4\,\mathrm{Hz}$$

Statorspenningen bir da

$$U_1 = U_{1N}\frac{f_1}{f_{1N}} = 230 \cdot \frac{25,4}{50} = 117\,\mathrm{V}$$

10.9 Strømbegrensing ved oppstart

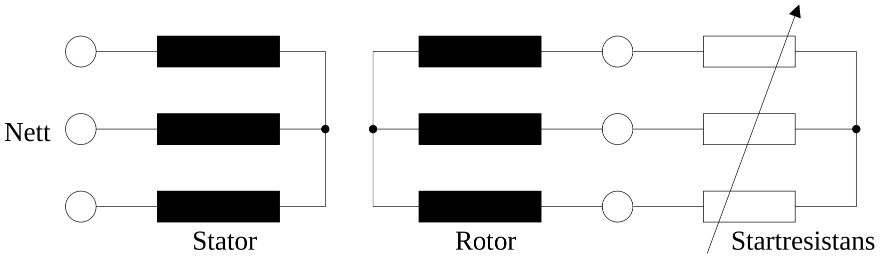
Ved oppstart (stillestående rotor), vil det utvikles en kraftig rotorstrøm. Denne laststrømmen vil føre til at statorstrømmen øker fra 4 til 9 ganger merkeverdi, med 6 ganger merkestrøm som en typisk verdi. Etter hvert som motoren drar seg opp i turtall, vil strømmen avta, som vist på figur 10.28, og ved merketurtall n_N vil motoren trekke merkestrøm I_N. Ved direktestart av en asynkronmotor må en altså regne med en høy startstrøm og dimensjonere vern og tilførselsledninger ut fra det.



Figur 10.28: Statorstrøm som funksjon av turtall

Sleperingsmotstand

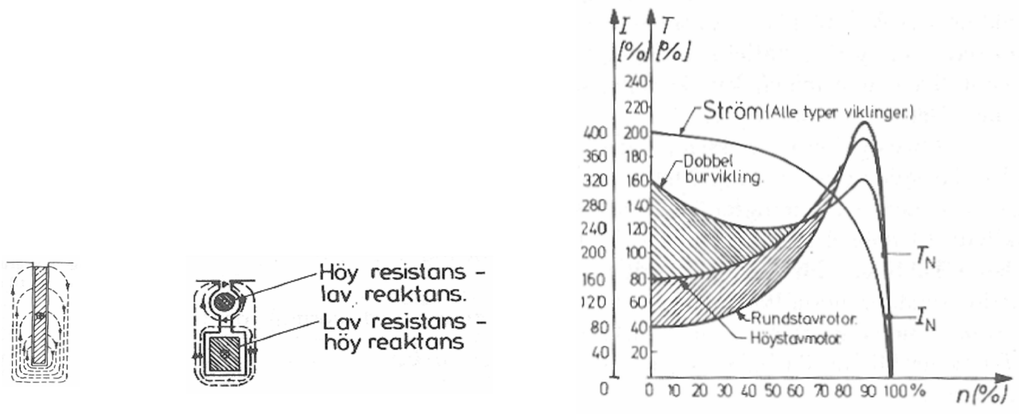
En måte å redusere startstrømmen på, er å koble en ytre startmotstand i rotorkretsen, slik det er vist på figur 10.29. Derved vil en redusere startstrømmen. I tillegg vil en få et høyere startmoment, slik figur 10.23 viser. Det betinger selvsagt at man benytter en sleperingsmaskin.



Figur 10.29: Sleperingsmaskin med startresistans

Strømfortrengningsrotor

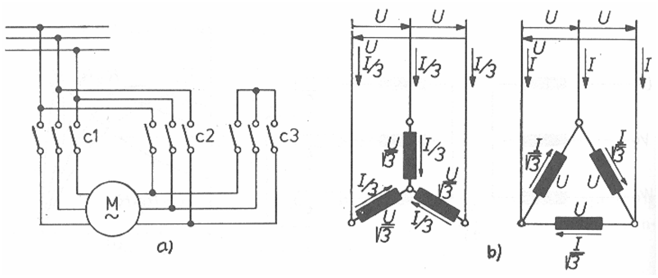
Selv om det ikke er mulig å koble en startmotstand inn i rotorkretsen på en burviklet rotor, er det likevel mulig å endre rotorresistansen. Dette oppnås ved en spesiell måte å konstruere rotorviklingene. Ved vanlige rundstavviklinger vil momentkarakteristikken være gitt ved formel (10.32). Figur 10.30 viser to alternative måter å utføre viklingene på. Høystavviklingen til venstre er lagt på en slik måte i et spor i rotorjernet at den nedre delen av viklingen har større lekkfluks (og reaktans) enn den øvre. Ved stillestående rotor vil rotorfrekvensen være høy, og strømmen vil presses til å gå i den øvre delen av lederen. Dermed vil det effektive tverrsnittet minke, og resistansen øker ved lavt rotorturtall. Dobbel burvikling (midt på figur 10.30) bygger på et lignende prinsipp. Den består av to viklinger, en øvre med høy resistans og lav reaktans, og en nedre med lav resistans og høy reaktans. Ved oppstart tvinges størstedelen av rotorstrømmen til å gå gjennom den høyohmige lederen. Ved merkedrift er rotorfrekvensen lav, og da går rotorstrømmen gjennom den lavohmige lederen.
Til høyre på figur 10.30 vises momentkarakteristikkene for de ulike typer rotorviklinger.



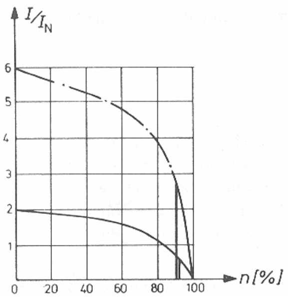
Figur 10.30: Prinsipp for strømfortrengningsrotor

Stjerne-trekantvender

Startstrømmen reduseres med en Y-D-vender (figur 10.31). Ved oppstart legges c1 og c3 inn (stjernekobling). Viklingene er da være stjernekoblet, og startstrømmen er moderat, fordi statorviklingene påtrykkes fasespenning og fordi linjestrøm er lik fasestrøm. Når motoren nærmer seg merketurtall, legges c3 ut og c2 kobles inn (trekantkobling). Da vil linjestrømmene tredobles, fordi viklingene påtrykkes linjespenning og fordi linjestrøm er større enn fasestrøm. Figur 10.32 illustrerer dette.



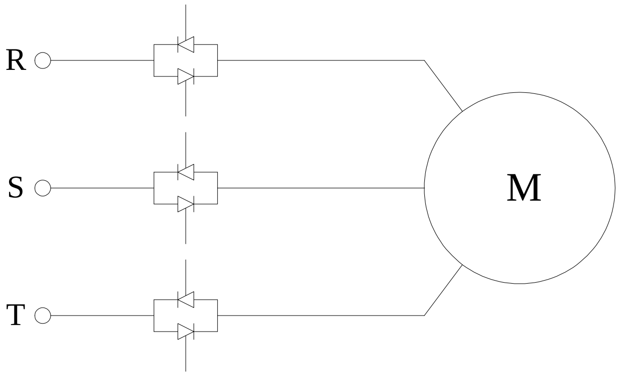
Figur 10.31: Motor med Y-D-vender



Figur 10.32: Motorstrøm som funksjon av turtall ved d-kobling og y-kobling

Mykstarter

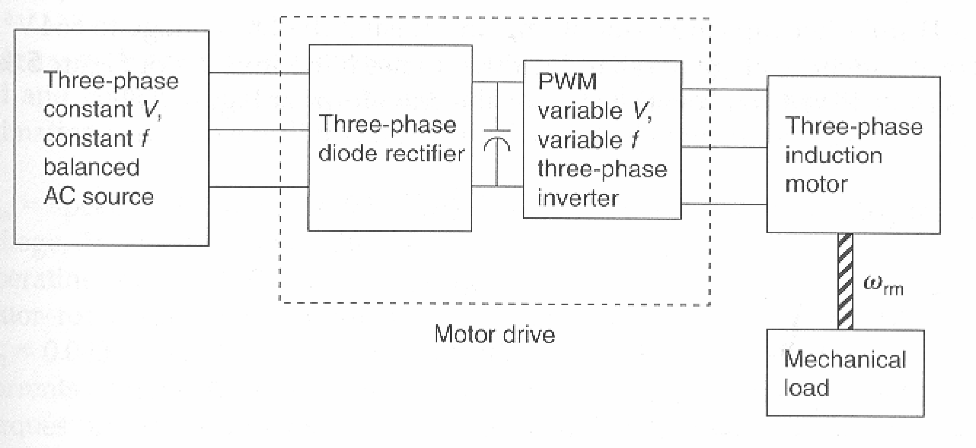
En annen måte å redusere startstrømmene og startmomentet på, er å benytte en såkalt mykstarter. Prinsippet er vist på figur 10.33. I hver motorfase står det to tyristorer i antiparallell. Ved oppstart reduseres styrevinkelen gradvis fra 180 til $0°$, og dermed begrenses såvel statorspenningene som linjestrømmene ved oppstart. Ulempen er at innsnittstyring genererer strømmer med et høyt innhold av overharmoniske. Siden dette bare skjer under selve oppstarten, er strømkvaliteten et kortvarig og forbigående problem.



Figur 10.33: Prinsippskisse for mykstarter

10.9.1 Frekvensomformer

Den beste måten å starte en asynkronmaskin på, er naturligvis ved hjelp av en frekvensstyring, som vist på figur 10.27. Gjennom å øke nettfrekvensen gradvis, vil man kunne gjøre en oppstart hvor sakkingen og dermed også rotorstrømmen hele tiden holdes på et moderat nivå. En må da endre statorfrekvensen så langsomt at motoren rekker å dra seg opp i turtall. Figur 10.34 viser skjematisk oppbygging av en frekvensstyring.



Figur 10.34: Blokkdiagram av frekvensstyring av motor

Styringen mates fra nettet (konstant spenning, konstant frekvens og balanserte spenninger). En toveis sekspuls likeretterbro leverer likestrøm til en DC mellomkrets med en glattekondensator . Motoren forsynes av en pulsbreddemodulert vekselretter med variabel spenning og frekvens.

Det er fortsatt ganske vanlig å forsyne motoren med en ufiltrert pulsbreddemodulert spenning. Den store induktansen i motoren vil likevel begrense rippelet i statorstrømmen. Motorens høye treghetsmoment gjør at den vil gå jevnt, selv om drivmomentet vil variere i takt med strømrippelet. Det er noen store ulemper med å bruke en ufiltrert utgangsspenning fra vekselretteren:

- Dersom svitsjefrekvensen ligger under 10kHz, vil motoren gi fra seg en sjenerende pipelyd på grunn av det pulserende momentet.
- Ufiltrert spenning gir uønskede jordstrømmer og økt lagerslitasje.
- Den pulsbreddemodulerte spenningen kan forårsake radiostøy og krever god skjerming av motorkabelen.

Ved å utstyre utgangen på vekselretteren med et lavpassfilter, oppnås en tilnærmet sinusformet utgangsspenning.

Eksempel 9 *En* 4*-polig kortslutningsmotor har et merketurtall* $n_N = 1470$ *o/min når den er tilkoblet* 230 *V med en frekvens på* 50 *Hz. En frekvensstyring som består av en diodelikeretter og en pulsbreddemodulert vekselretter, forsyner motoren. Mellomkretsen inneholder en stor glattekondensator. Beregn mellomkretsspenningen når en antar at kondensatoren er så stor at spenningsrippelet kan neglisjeres.*

Beregn statorfrekvens og –spenning når motoren skal gå med et turtall på 900 *o/min. Lastmomentet er konstant, uavhengig av turtallet. Vekselretternes kontrollkrets har et triangelsignal med en amplitude på* $2,5$ *V. Hva blir referansesignalets amplitude ved dette turtallet?*
Gjør samme beregninger ved et turtall på 400 o/min.

Løsning:
For en likeretter med en stor glattekondensator, vil likespenningen være lik toppverdien av den ufiltrerte vekselspenningen, som tilsvarer maksimal sperrespenning:

$$U_d = \sqrt{2}U_{1N} = \sqrt{2} \cdot 230 = 325\,\mathrm{V}$$

Synkront turtall ved 50 Hz er

$$n_{s,50} = \frac{60 \cdot 50}{2} = 1500 \text{ o/min}$$

Det betyr at motoren sakker med $1500 - 1470 = 30$ o/min ved merkedrift.
Hvis motoren skal gå med 900 o/min, må synkront turtall være

$$n_s = 900 + 30 = 930 \text{ o/min}$$

Det tilsvarer en statorfrekvens på

$$f_1 = n_s \frac{p}{60} = 930 \cdot \frac{2}{60} = 31\,\mathrm{Hz}$$

Formel (10.43) slår fast at statorspenning og –frekvens må være proporsjonale. Ved 31 Hz må dermed klemmespenningen være:

$$U_{1,31} = 230 \cdot \frac{31}{50} = 143\,\mathrm{V}$$

Sammenhengen mellom likespenning, linjespenning og kontrollsignalene er gitt ved følgende formel:

$$U_L = U_d \frac{\sqrt{3}}{2\sqrt{2}} \frac{U_{control}}{U_{tri}}$$

Denne løses med hensyn på kontrollsignalets amplitude:

$$U_{control} = \frac{2\sqrt{2}U_{1,31}}{\sqrt{3}U_d} U_{tri} = \frac{2 \cdot \sqrt{2} \cdot 143}{\sqrt{3} \cdot 325} \cdot 2,5 = 1,8\,\mathrm{V}$$

Hvis motoren skal gå med 400 o/min, må synkront turtall være

$$n_s = 400 + 30 = 430 \text{ o/min}$$

Det tilsvarer en statorfrekvens på

$$f_1 = n_s \frac{p}{60} = \frac{430}{30} = 14{,}3\text{Hz}$$

Da blir klemmespenningen:

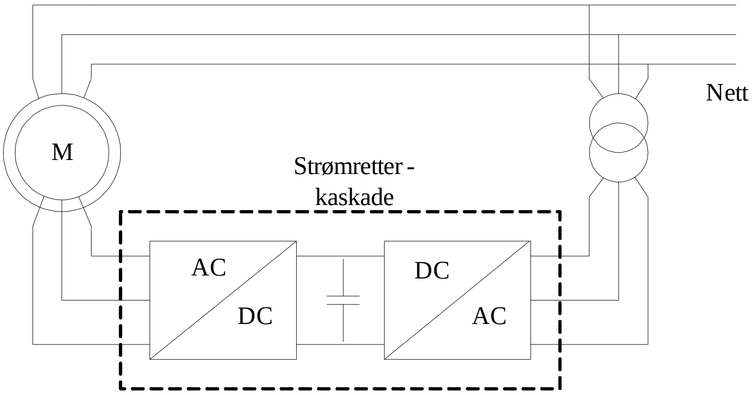
$$U_{1,14,3} = 230 \cdot \frac{14{,}3}{50} = 65{,}9\text{V}$$

Referansesignalets amplitude blir:

$$U_{control} = \frac{2\sqrt{2}U_{1,14,3}}{\sqrt{3}U_d} U_{tri} = \frac{2 \cdot \sqrt{2} \cdot 65,9}{\sqrt{3} \cdot 325} \cdot 2,5 = 830\,\text{mV}$$

Figur 10.23 viser virkningene av å koble en ytre motstand i rotorkretsen til en sleperingsmaskin. Ulempene har vi allerede sett på: Motoren må benytte sleperinger, og det vil være effekttap i denne rotormotstanden. Hvis man likevel velger å benytte en sleperingsmaskin, er det mulig å benytte en krets som reduserer rotortapene til et minimum. En likeretter som styres slik at strøm og spenning er i fase med hverandre, vil "ses" av kilden som en resistans. Dette kalles populært for en tapsfri resistans, siden den opptatte effekten ikke blir omdannet til varme, men kan lagres eller videredistribueres. Noen svitsjetap må man likevel regne med.

Dersom man kobler en strømretterkaskade inn i rotorkretsen, som vist på figur 10.35, kan man styre maskinen med sakkingsregulering, samtidig som rotortapene holdes på et minimum.



Figur 10.35: Sleperingsmaskin med strømretterkaskade i rotorkretsen

Rotorkretsen er tilkoblet en styrt likeretter som igjen forsyner en vekselretter som står tilkoblet nettet via en transformator. Ved normal drift er rotorspenningen moderat, og transformatoren sørger for å bringe vekselretterens utgangsspenning nærmere rotorspenningen. Ved vanlige motordrifter vil en frekvensstyring være en enklere løsning. For store maskiner anvendes systemet en del, blant annet såkalte dobbeltmatede vindturbiner. I slike vil hoveddelen av effekten leveres direkte fra stator, mens en del av effekten leveres fra rotor (ca. 20 – 25%).

10.10 Driftsforstyrrelser

Frekvens- eller spenningsdrift

To andre forhold som også kan virke negativt inn, er avvik i nettspenning eller frekvens for en maskin som er koblet direkte til nettet. Dersom nettspenningen øker uforholdsmessig mye (mer enn $5 - 10$ % av merkeverdi), vil magnetiseringsstrømmen også øke betraktelig, og dermed også linjestrømmen. Dersom nettspenningen faller, vil feltet svekkes, og rotorstrømmen må øke tilsvarende for å opprettholde momentet. Resultatet er at linjestrømmen også i dette tilfelle øker.

Dersom frekvensen faller, vil fluksen øke, fordi magnetiseringsreaktansen X_0 på figur 8.14 reduseres, og dermed øker magnetiseringsstrømmen i_{0q}. Dersom frekvensen stiger, vil fluksen falle tilsvarende, og rotorstrømmen øker for å opprettholde momentet. Det betyr at også frekvensen bør ligge nært opp til merkeverdi.

Ved en frekvensstyring vil ikke slike overbelastninger oppstå, fordi nettspenning og –frekvens endres proporsjonalt, og da vil magnetiseringsstrøm og fluks være konstante.

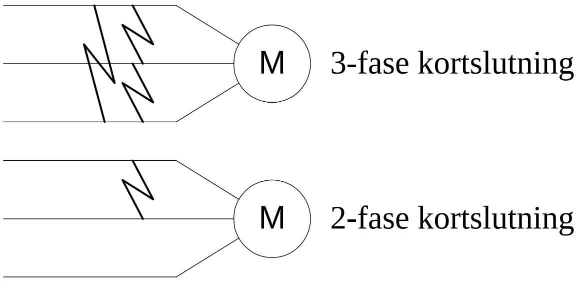
Ustabilitet i nettet skyldes gjerne at overføringskapasiteten er for dårlig eller at produksjonskapasiteten er for liten. Resultatet er at nettspenningen og/eller frekvensen faller. I begge tilfelle vil laststrømmene i direkte tilkoblet motorlast øke, og et allerede presset nett vil bli utsatt for ytterligere påkjenninger. I løpet av kort tid vil mange motordrifter stanse, og i verste fall ender det hele opp med total strømstans.

Overharmoniske

Dersom klemmespenningen inneholder overharmoniske komponenter, vil det bidra til å øke tapene i maskinen, uten at ytelsen økes. De femteharmoniske spenningene har omvendt fasefølge og vil skape et dreiefelt som roterer baklengs med fem ganger synkront turtall. De sjuendeharmoniske spenningene skaper et dreiefelt som roterer forlengs med sju ganger synkront turtall. Derfor skaper små harmoniske spenningskomponenter betydelige harmoniske strømmer. Disse overharmoniske linjestrømskomponentene kan påvirke annet utstyr og vil dessuten medvirke til at nettspenningen blir ytterligere forvrengt.

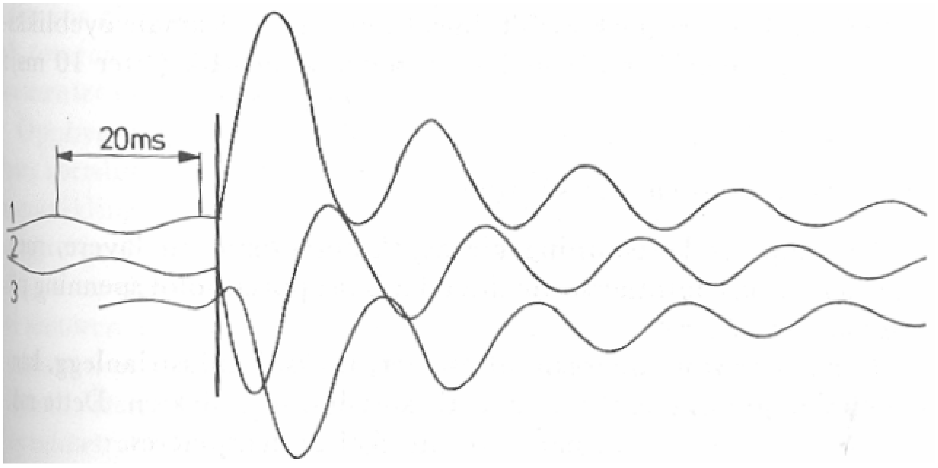
Kortslutning

En annen driftsforstyrrelse en bør ta hensyn til, især ved store maskiner, er asynkronmaskinens transiente kortslutningsstrøm. Dersom en trefase kortslutning inntreffer mellom motoren og nettet, vil maskinen opprettholde indusert spenning, fordi induserte strømmer i rotor vil opprettholde fluksen, og det tar alltid en viss tid å bygge ned en fluks i en stor magnetisk masse. Treghetsmomentet i rotor og last sørger for at turtallet gradvis faller. Resultatet er at den induserte spenningen i stator driver en kortslutningsstrøm som for store maskiner kan vedvare i $0,1 - 0,2$ sekunder. Figur 10.37 viser et oscillogram av kortslutningsstrømmer fra en 55 kW asynkronmotor.



Figur 10.36: 3-fase og 2-fase kortslutning på tilførselskabel til asynkronmaskin

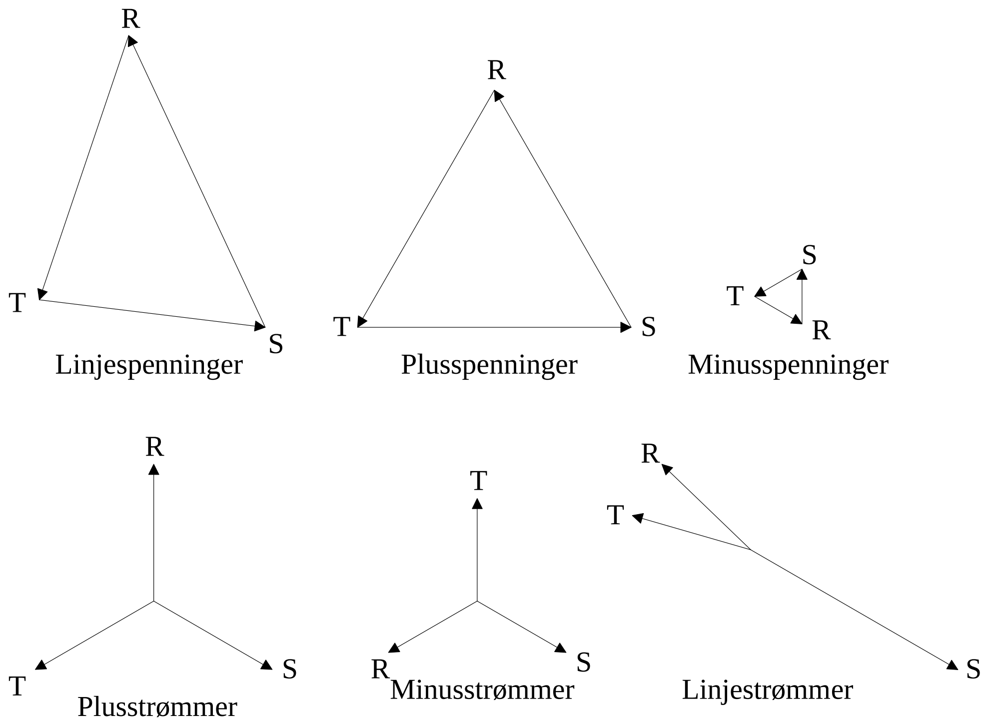
Dersom kortslutningen er topolet, vil kortslutningsstrømmen bli lavere, men fluksen vil vedvare, siden det stadig mates spenning inn på klemmene. For svært store maskiner bør en ta hensyn til disse forholdene ved dimensjonering av anlegget. Figur 10.36 illustrerer dette forholdet.



Figur 10.37: Oscillogram av kortslutningsstrømmer fra en asynkronmotor

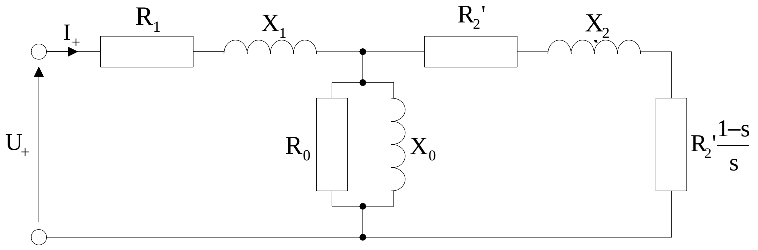
Usymmetri

Som nevnt i kompendiet Strømrettere og transformatorer", kan ubalanserte spenninger eller strømmer dekomponeres i symmetriske komponenter. Dersom en asynkronmaskin påtrykkes ubalansert nettspenning, kan en tenke seg et sett symmetriske trefasespenninger som roterer i motorens dreieretning og et sett som roterer i motsatt retning. Dette er illustrert i figur 10.38.
Plussystemet vil se en motor som går med noen få prosent sakking og vil trekke en strøm som ligger rundt merkeverdi. Minussystemet vil se en motor som går baklengs (bremsedrift) og vil trekke en høy strøm i forhold til spenningsnivået. Dette er fremstilt i figur 10.39. Resultatet er at usymmetriske trefasespenninger gir enda mer usymmetriske linjestrømmer, slik det fremkommer av figur 10.38. Den høye sakkingen gjør dessuten at minusstrømmene er sterkt induktive. Usymmetrien i strømmen

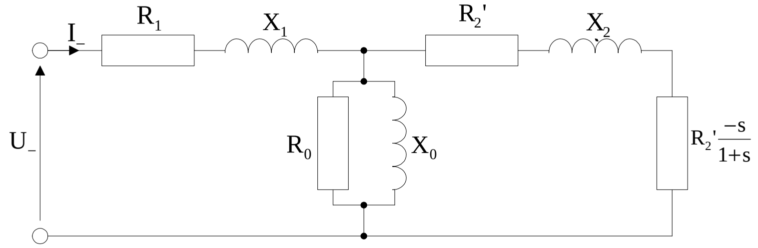


Figur 10.38: Usymmetriske klemmespenninger og resulterende usymmetri i motorstrømmene.

er gjerne $5 - 10$ ganger større enn usymmetrien i spenningen, og varmeutviklingen i rotor vil øke betydelig. Ved en usymmetri i spenningen på 15 % eller mer, vil ikke motoren være i stand til å drive noen nevneverdig last.



Plussystem

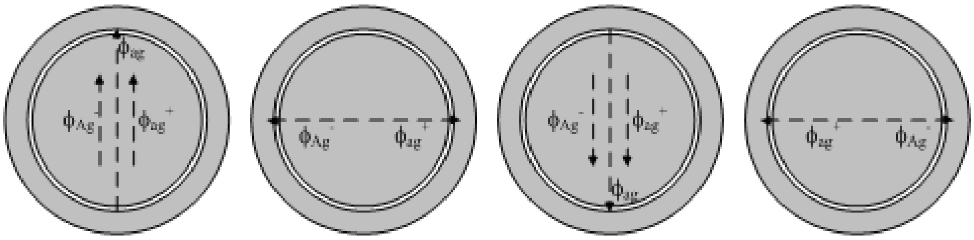


Minussystem

Figur 10.39: Faseekvivalenter for pluss- og minussystemet

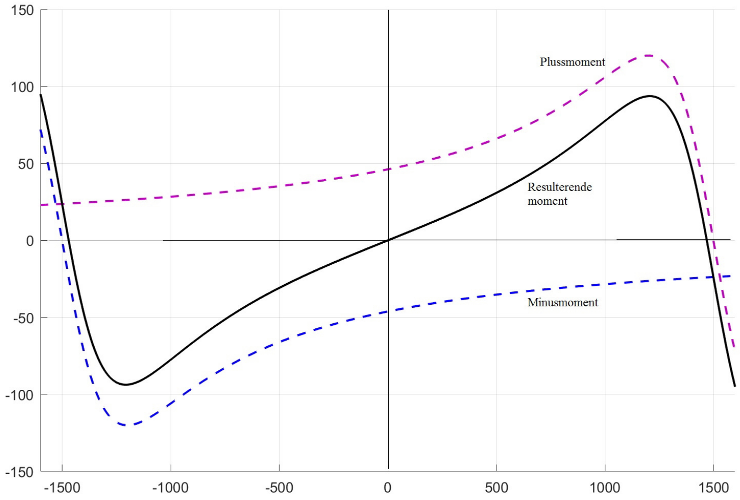
10.11 Enfasedrift

Den mest ekstreme usymmetrien oppstår dersom en fase faller ut. Da vil maskinen magnetiseres av en pulserende linjespenning som kan modelleres som to motroterende trefasespenninger. Resultatet er to like store luftgapsflukser som roterer i motsatt retning. Til sammen utgjør de den pulserende fluksen som vil ligge over luftgapet. Dette er vist på figur 10.40.



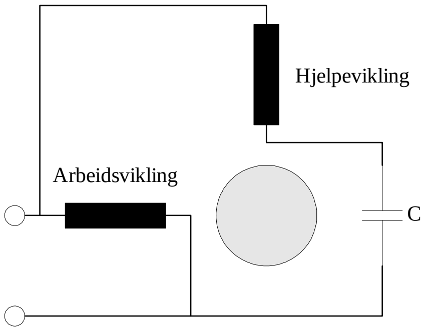
Figur 10.40: Pulserende luftgapsfluks modellert som motroterende flukskomponenter

En stillestående asynkronmotor som har mistet en fase, vil ikke ha noe startmoment. Hvis vi drar den i gang, uansett retning, vil den dra seg opp i turtall. Den vil imidlertid ikke klare å trekke særlig mye last. Figur 10.41 viser momentkurven for en asynkronmaskin i enfasedrift. En ser at så snart maskinen får turtall i en retning, vil drivmomentet i denne retningen dominere mer og mer. Ved stillstand er begge momentene like store, og da vil det resulterende momentet være lik null.

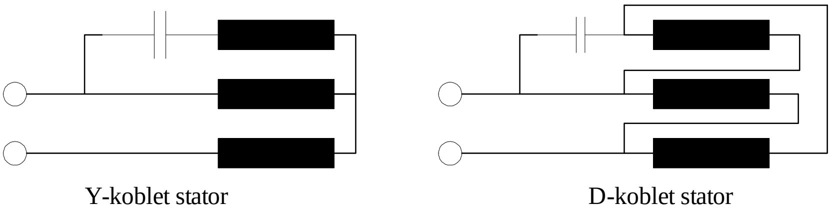


Figur 10.41: Resulterende moment for en asynkronmaskin i enfasedrift

En måte å bedre momentkarakteristikken, er å benytte en enfasemotor med en arbeidsvikling og en hjelpevikling. Den prinsipielle oppbyggingen er vist på figur 10.42. I realiteten er dette en tofasemotor, fordi kondensatoren i hjelpefasen forskyver denne fasestrømmen nitti grader foran strømmen i arbeidsviklingen. Disse to viklingene setter opp et dreiefelt på samme måte som for en trefasemaskin. Ulempen med den løsningen som er benyttet på figur 10.42, er at man må benytte en spesiell type motor. Hvis man ønsker å bruke en vanlig trefasemaskin i enfasedrift, kan man gjøre det ved hjelp av såkalt Steinmetzkobling med en hjelpekondensator. Denne koblingsmåten er vist på figur 10.43. Kondensatoren sørger da for at den tredje fasestrømmen ligger 90° forskjøvet i forhold til de to andre. Dermed vil motoren få startmoment.



Figur 10.42: Topolig enfasemotor med arbeidsvikling og hjelpevikling

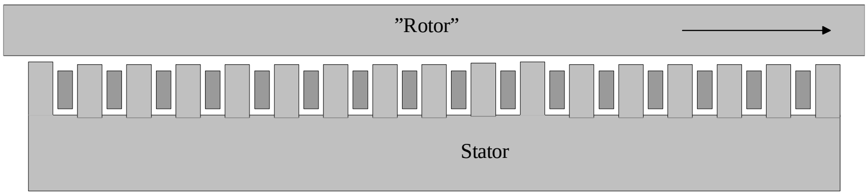


Figur 10.43: Steinmetzkobling

10.12 Andre motortyper

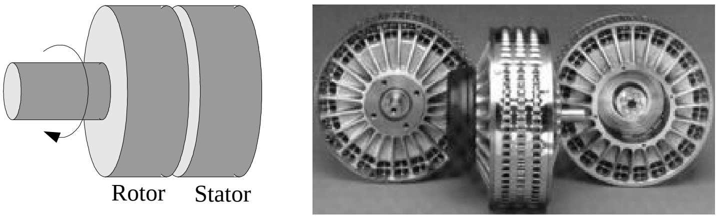
Det finnes et vell av utførelser og anvendelser av asynkronmaskinen. Vi skal bare se på noen få spesielle utførelser her.

Dersom en ”bretter ut” stator slik at jernet danner en langsgående skinne med spor til viklingene, har en prinsippet for en lineærmotor som er vist på figur 10.44. Hvis en påtrykker trefasespenninger på statorviklingene, vil det oppstå en fluks som glir bortover langs den rettlinjede statoren. Plasserer man en bevegelig del, ”rotoren”, like over stator, og denne delen består av elektrisk ledende materiale, vil de induserte spenningene gjøre at den trekkes langs statorfeltet, på samme måte som rotoren i en asynkronmaskin. Den bevegelige delen løftes litt opp fra stator ved hjelp av ruller eller magnetisk levitasjon. Lineærmotorer brukes blant annet i svevetog og berg-og-dal-baner.



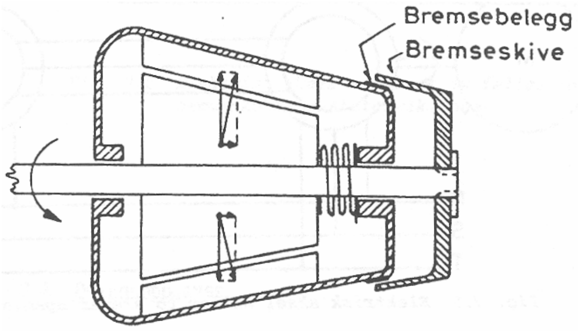
Figur 10.44: Prinsippskisse for lineærmotor

En annen spennende måte å bygge opp en asynkronmotor, er i form av skivemotoren. Til venstre på figur 10.45 vises en prinsippskisse. I motsetning til den vanlige asynkronmotoren, er stator og rotor plassert som skiver ved siden av hverandre. Luftgapsfluksen går dermed aksielt og ikke radielt. Dette gir en svært kompakt utførelse, som vist til høyre på figuren. Skivemotoren brukes mye i elbiler.



Figur 10.45: Prinsippskisse og bilde av skivemotor

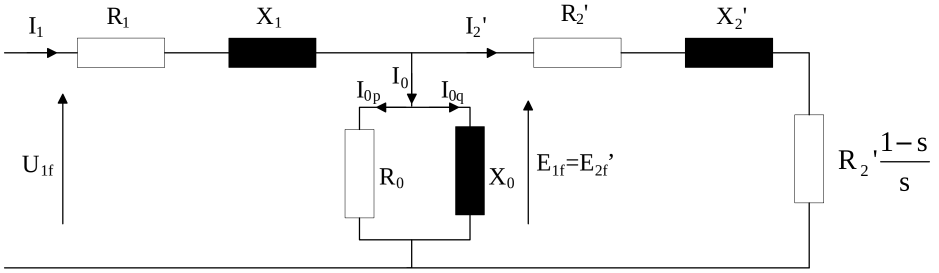
Noen ganger er det nødvendig å aktivere en mekanisk brems når en slår av motoren, for eksempel i en elektrotalje. Hvis ikke, ville rotoren løpe fritt rundt og lasten havnet i bakken hver gang strømmen ble slått av. Figur 10.46 viser prinsippskissen for en slik bremsemotor. Når motoren er utkoblet, sørger ei fjær for å presse bremseskiven mot et bremsebelegg på motorhuset. Når stator magnetiseres, vil rotor trekkes litt inn, og bremseskiven frigjøres. Dermed kan motoren løpe rundt, helt til spenningen kobles ut, og bremsen aktiveres igjen.



Figur 10.46: Prinsippskisse for bremsemotor

10.13 Øvingsoppgaver

1. Regn ut synkront turtall for en maskin med ett polpar tilkoblet $50\,\mathrm{Hz}$ nett. Hva blir synkront turtall for en maskin med 6 poler tilkoblet $60\,\mathrm{Hz}$ nett?
2. En maskin med to polpar er tilkoblet $50\,\mathrm{Hz}$ og går med 1420 o/min. Beregn sakkingen.
3. Hva blir rotorfrekvensen for maskinen i oppgave 2?
4. Figur 10.47 viser et fullstendig ekvivalentskjema for asynkronmaskinen. Hva representerer de ulike delene av skjemaet?



Figur 10.47: Faseekvivalent for asynkronmaskin

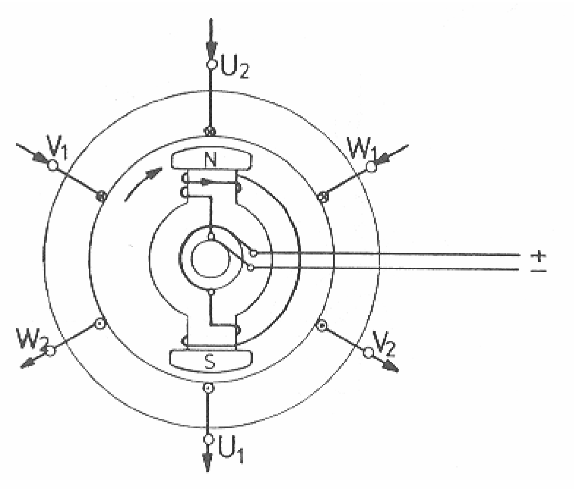
5. Tegn en figur som viser effektflyten og tapene i en asynkronmaskin.
6. En $5,0\,\mathrm{kW}$ maskin går med en sakking på $2,5\%$. Beregn rotortapet.
7. Maskinen i oppgave 6 er tilkoblet et $400\,\mathrm{V}$ $50\,\mathrm{Hz}$ nett og har tre polpar. Kippsakkingen er på 20%. Beregn kippmomentet og startmomentet.
8. Regn ut kippmomentet og startmomentet for maskinen i oppgave 6 og 7 hvis spenningen faller til $350\,\mathrm{V}$.
9. Maskinen i oppgave 6 - 8 har samlede tap på $850\,\mathrm{W}$. Beregn virkningsgraden.
10. Hva kjennetegner asynkronmaskinens tre driftsformer?
11. Maskinen i oppgave 6 er en sleperingsmaskin med en rotorresistans på $1,0\,\Omega$. Hvor stor ytre sleperingsmotstand må benyttes for at maskinen skal gå med 900 o/min dersom lasten har konstant moment?
12. Det benyttes en frekvensomformer for å drive maskinen i oppgave 6 med turtall og moment som angitt i oppgave 11. Hvilken frekvens og spenning må omformeren ha på utgangen?
13. Forklar prinsippet bak strømfortrengning i høystavviklinger på en burviklet asynkronmaskin.
14. En vanlig trefase asynkronmaskin forsynes fra et enfasenett. Hvordan kan maskinen kobles for at den skal utvikle startmoment?
15. Hva er årsaken til at en asynkronmaskin i motordrift kan fungere som spenningskilde ved kortslutning i nettet?

11 Synkronmaskinen

11.1 Oppbygging og virkemåte

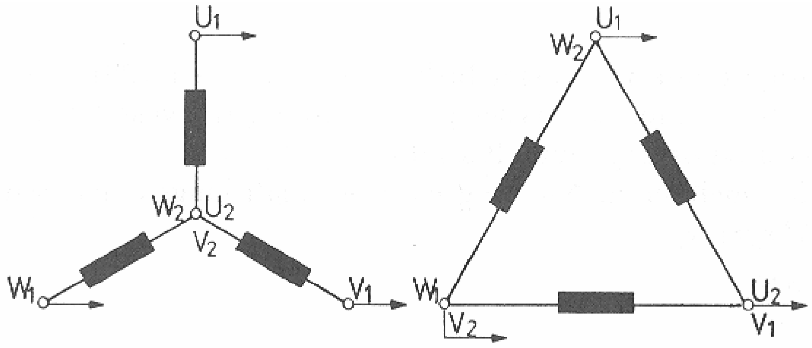
Stator er bygget opp på samme måte som asynkronmaskinen. Den største prinsipielle forskjellen er at rotoren i en synkronmaskin inneholder en likestrømsvikling som mates via sleperinger og børster, slik det er vist på figur 11.1. I en asynkronmaskin hentes magnetiseringsstrømmen fra statorkretsen, med mindre den er dobbeltmatet, mens en synkronmaskin magnetiseres av rotor, også kalt polhjulet. Siden luftgapsfluksen vil være bundet til rotor, vil også luftgapsfeltet alltid følge rotor. Siden maskinen alltid roterer synkront med dreiefeltet, kalles den en synkronmaskin. En nettilkoblet synkronmaskin vil alltid rotere med samme turtall som nettfrekvensen og polpartallet tilsier:

$$n_r = n_s = \frac{60 \cdot f}{p} \tag{11.1}$$



Figur 11.1: Prinsippskisse av synkronmaskin

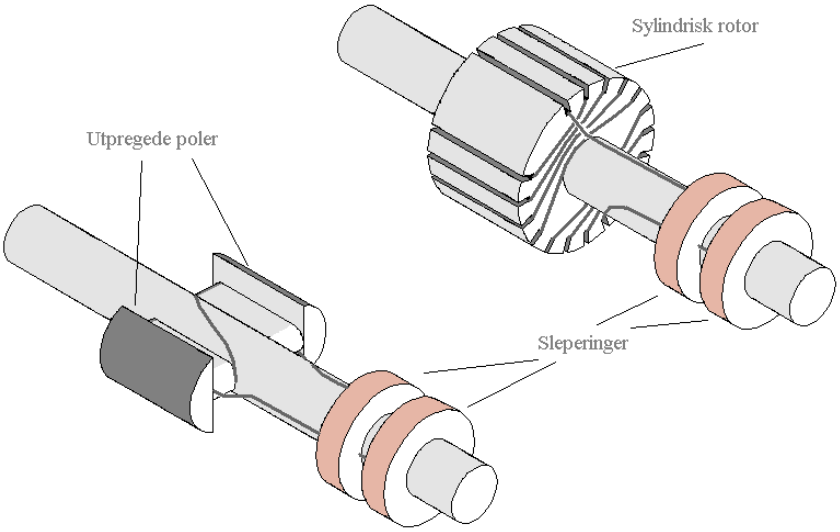
I likhet med asynkronmaskinen, kan synkronmaskinens statorviklinger (ankerviklinger) kobles enten i stjerne eller trekant. Det mest vanlige er å koble viklingene i stjerne for å fjerne den tredjeharmoniske spenningskomponenten i de induserte statorspenningene fra maskinens linjespenninger. Figur 11.2 viser statorviklingene koblet i stjerne (til venstre) og i trekant (til høyre).



Figur 11.2: Koblingsmåter for synkronmaskinens ankerviklinger

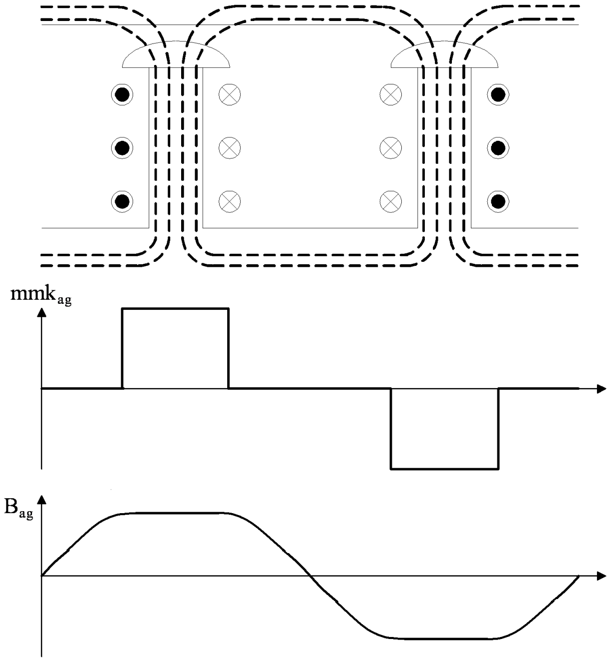
11.2 Rotortyper

Figur 11.3 viser de to rotortypene som benyttes i synkronmaskinen. Ved høye turtall (1500 eller 3000 o/min) benyttes gjerne en sylindrisk rotor, også kalt turborotor, hvor rotorviklingen er lagt i spor i rotorjernet. Dersom rotorviklingen legges som spoler med avrundede polsko, har vi en rotor med utpregede poler, og denne brukes gjerne ved lave turtall (100 – 500 o/min).



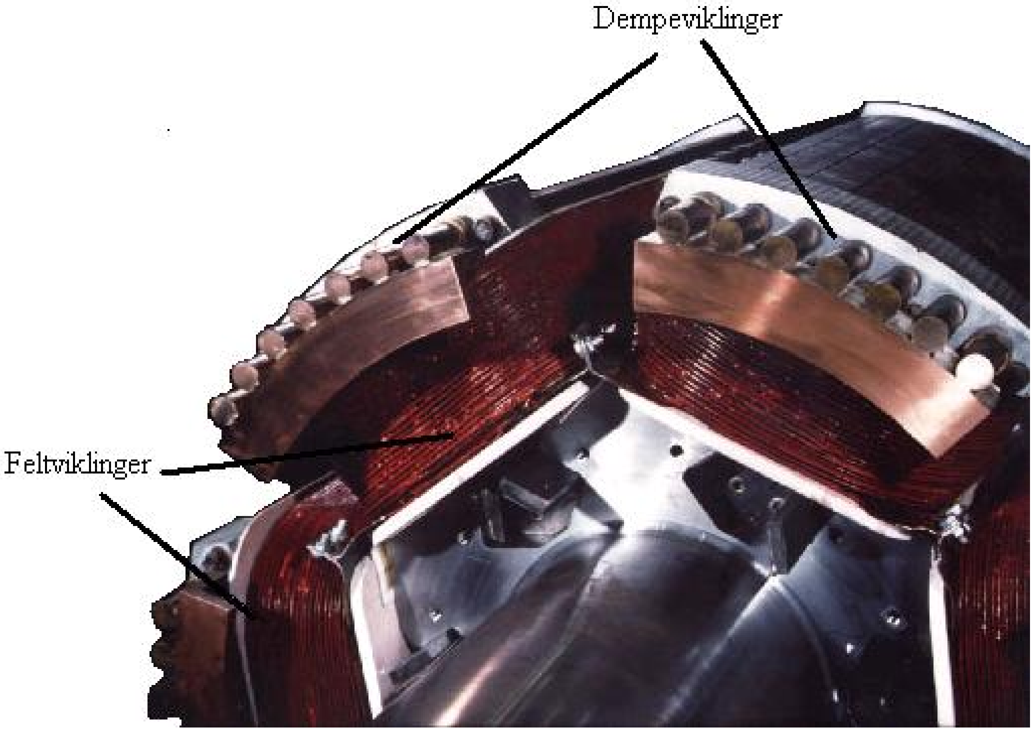
Figur 11.3: Rotortyper for synkronmaskin

For en sylindrisk rotor vil den magnetomotoriske kraften ha en tilsvarende trappeform som vist på figur 10.8. Luftgapet gjør at fluksen får en ganske sinusformet fordeling. For rotorer med utpregede poler vil den magnetomotoriske kraften bli som vist på figur 11.4. Dette burde gi en svært firkantet fluksfordeling, men den avrundede formen på polskoene gjør at fluksfordelingen også i dette tilfellet blir noe mer sinusformet.



Figur 11.4: Fluksfordeling over luftgapet i synkronmaskin med utpregede rotorpoler

Ute på polskoene er det vanlig å plassere noen kortsluttede ledere med stort tverrsnitt, de såkalte dempeviklingene, som vist på figur 11.5. Prinsippet er det samme som for en asynkronmaskin med burviklet rotor. Hensikten med disse dempeviklingene er å dempe pendlinger i maskinen. Etter en forstyrrelse kan en oppleve at rotor går ujevnt i forhold til det synkrone dreiefeltet, og da vil dempeviklingene utvikle et moment som demper disse såkalte polhjulspendlingene, slik at rotor får en jevn gange.



Figur 11.5: Rotor med feltviklinger, dempeviklinger og utpregede poler

11.3 Indusert spenning

Når det roterende feltet som genereres av rotor skjærer statorviklingene, vil det induseres en spenning i disse. Formel (10.3) i uttrykker forholdet mellom indusert spenning i en leder, flukstettheten, lederens lengde og feltets (eller lederens) relative hastighet:

$$e = B \cdot \ell \cdot v \tag{11.2}$$

Siden turtallet holdes konstant ved konstant frekvens, vil også effektivverdien av hastigheten v være konstant. Da vil effektivverdien av indusert spenning kun være bestemt av flukstettheten, og dermed av fluksen. Indusert spenning i tomgang vil da være proporsjonal med fluksen:

$$E_{0f} = k \cdot \phi \tag{11.3}$$

Indusert spenning per fase kan også uttrykkes ved transformatorligningen:

$$E_{0f} = 4,44 \cdot f \cdot N_{eff} \cdot \phi_{\max} \tag{11.4}$$

hvor fluksens amplitudeverdi $\phi_{\max}$ er den eneste variable størrelsen. N_{eff} er det effektive vindingstallet og ikke det virkelige. N_{eff} kan være et desimaltall og vil alltid være noe mindre enn det virkelige vindingstallet. Årsaken er skrittforkorting og fasedreining som er omtalt i kapittel 11.4.

Fluksen er proporsjonal med magnetiseringsstrømmen I_m, og dermed kan formel (11.3) endres til:

$$E_{0f} = k \cdot I_m \tag{11.5}$$

Dette gjelder imidlertid bare så lenge jernet ikke går i metning.

Eksempel 1 *En synkrongenerator har en indusert tomgangsspenning* $E_0 = 15\,\mathrm{kV}$ *ved en magnetiseringsstrøm* $I_m = 150\,\mathrm{A}$. *Hva blir indusert spenning ved en magnetiseringsstrøm på* $180\,\mathrm{A}$*? Se bort fra metning i jernet.*

Løsning:
Ny indusert tomgangsspenning er

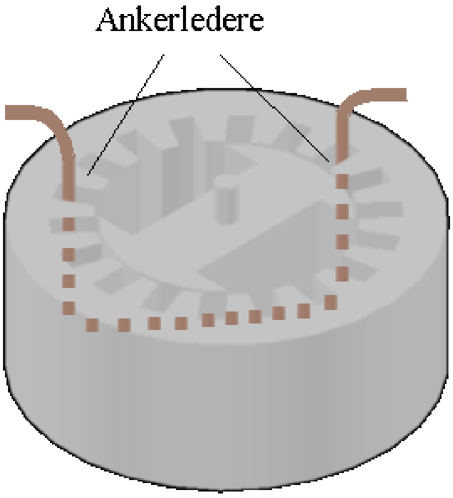
$$E_0 = 15000 \cdot \frac{180}{150} = 18\,\mathrm{kV}$$

11.4 Virkning av skrittforkorting, fasedreining og stjernekobling av statorviklinger

På grunn av ujevn fluksfordeling i luftgapet, kan indusert spenning i hver statorleder være svært forvrengt. I dette notatet analyseres virkningen av forkortet spoleskritt, seriekoblede vindinger som er fasedreid, og stjernekoblede statorspoler. Det tas utgangspunkt i en maskin med ett polpar og tre tørn per pol og fase.

Forkortet spoleskritt

Dersom to ledere som ligger diametralt motsatt kobles sammen til en statorvinding, vil spenningene være lik, men med motsatt fortegn. Den resulterende spenningen er summen av enkeltspenningene og vil ha samme forvrengte kurveform. Hvis de to sammenkoblede lederne ikke ligger diametralt motsatt, kan resultatet bli som på figur 11.6.



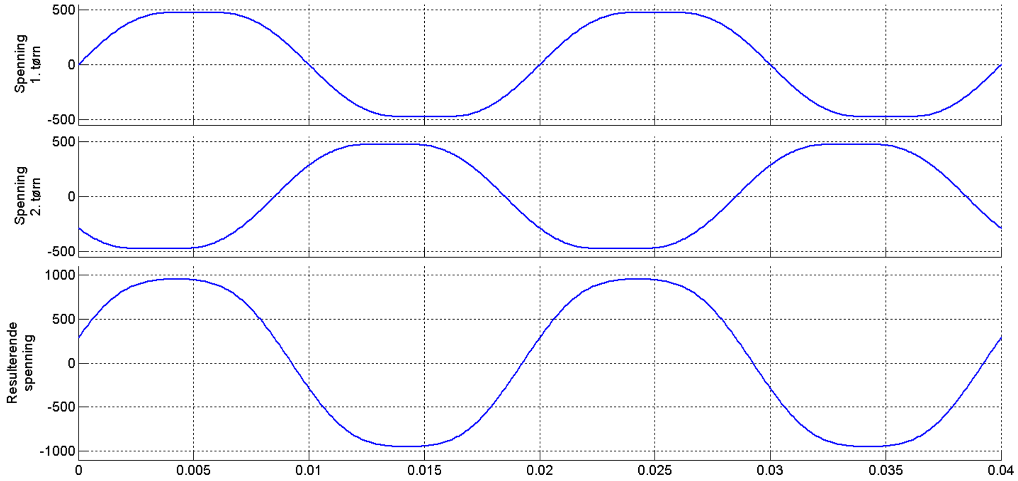
Figur 11.6: Forkortet spoleskritt

Følgen er at de to spenningene er litt mindre enn 180° forskjøvet. Dette fremkommer av figur 11.7. En ser at den resulterende spenningen har fått en noe bedre kurveform.

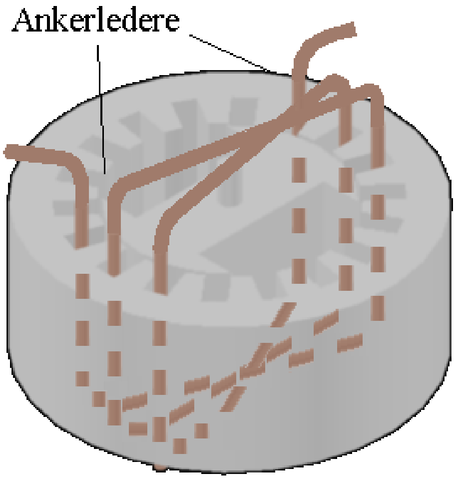
Fasedreide tørn

De tre tørnene i hver statorvikling kan legges i spor ved siden av hverandre. Dette fremgår av figur 11.8. Indusert spenning i hver vinding vil da være litt faseforskjøvet i forhold til nabovindingen.

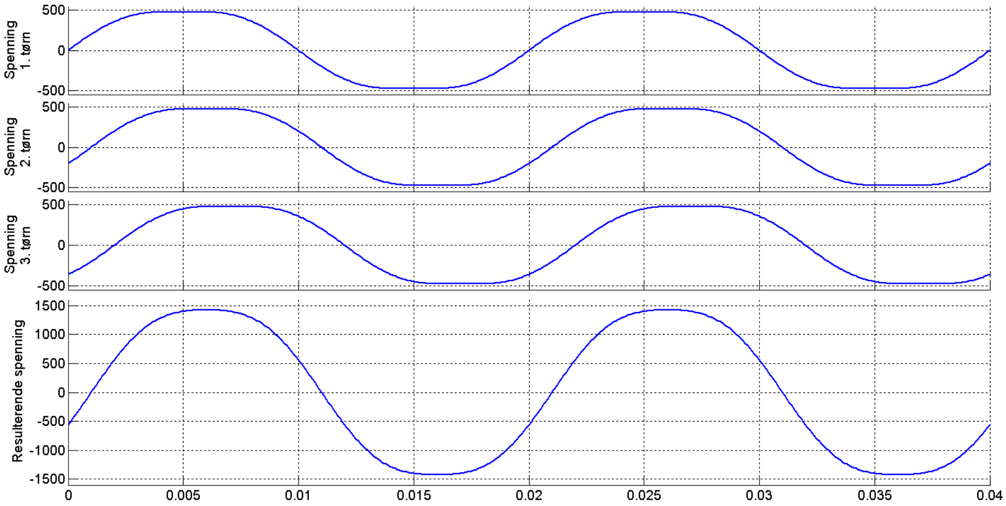
Den resulterende spenningen er vist på figur 11.9. Fasedreiningen gjør at spenningen for den seriekoblede viklingen får en betydelig bedre kurveform enn spenningen i hver faseleder.



Figur 11.7: Resulterende spenning ved skrittforkorting



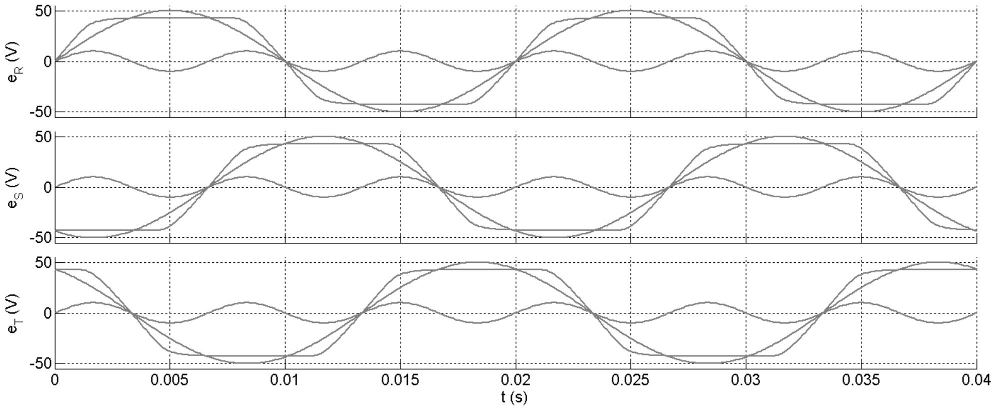
Figur 11.8: Fasedreide vindinger



Figur 11.9: Resulterende spenning ved fasedreide tørn

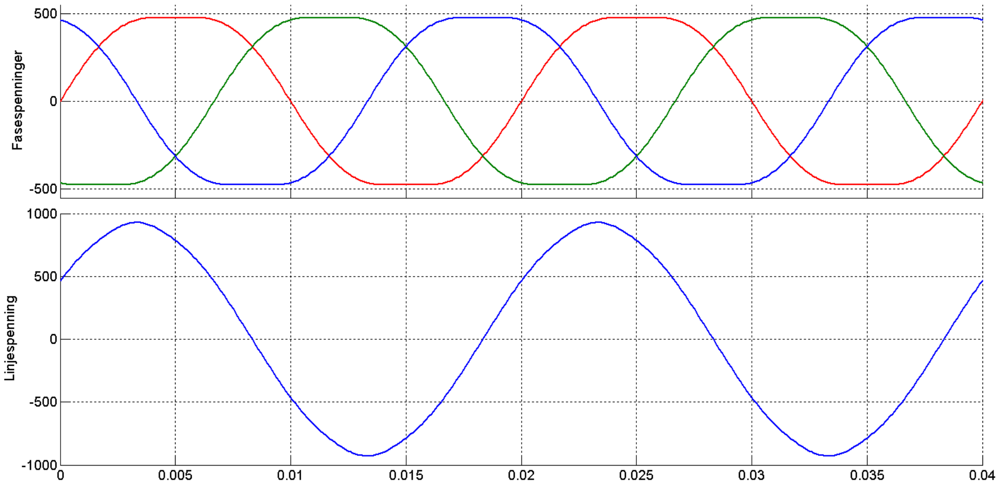
Stjernekobling

Den induserte spenningen i hver faseleder inneholder en betydelig mengde odde overharmoniske, med 3. harmoniske som den dominerende komponenten. Dette fremgår klart av figur 11.10. En kan her merke seg at den tredjeharmoniske komponenten er sammenfallende i hver fase.



Figur 11.10: Grunnharmoniske og tredjeharmoniske komponenter av indusert spenning i en ankerleder

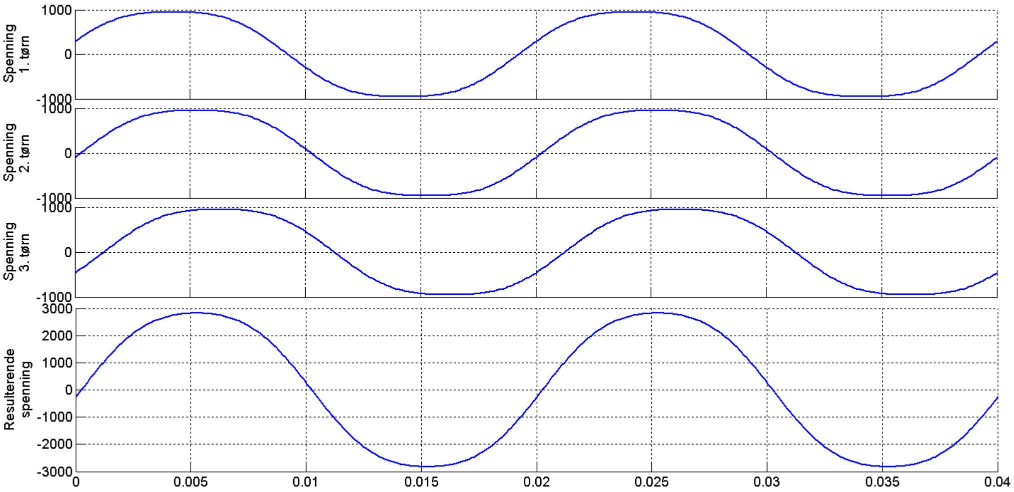
Dersom viklingene stjernekobles, vil derfor ikke 3. harmoniske forekomme i linjespenningene. En ser av figur 11.11 at stjernekoblingen gir en bedre spenningskvalitet. Dersom viklingene var trekantkoblet, ville linjespenningene ha samme forvrengte form som fasespenningene.



Figur 11.11: Fasespenninger og linjespenning ved stjernekobling

Kombinasjon av metodene

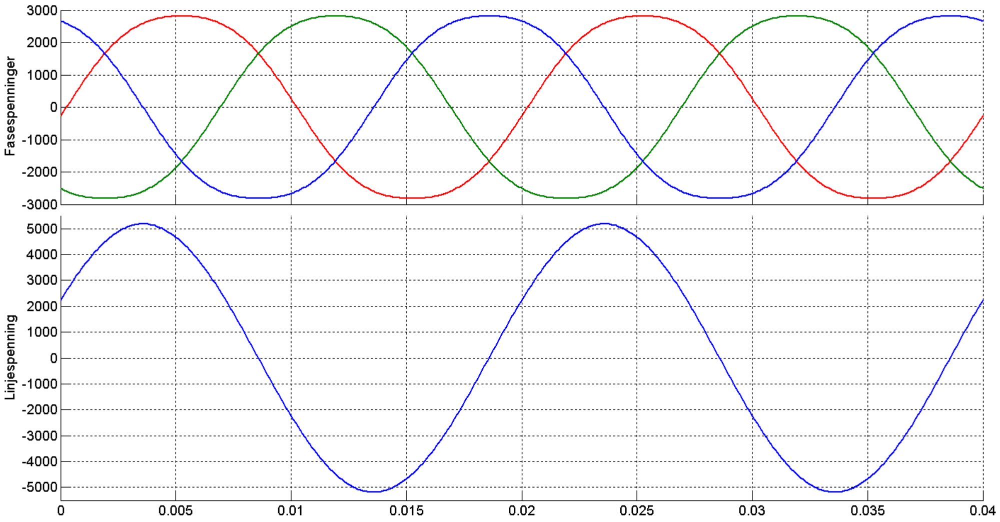
En ser at hver av de ovennevnte metodene bedrer formen på spenningskurvene. En kombinasjon burde derfor gi ytterligere forbedring.



Figur 11.12: Fasedreide tørn med skrittforkorting

Figur 11.12 viser at en kombinasjon av skrittforkorting og fasedreining gir en betydelig forbedring av spenningskurven.

Hvis fasespolene i tillegg kobles i stjerne, fjernes det som måtte være igjen av 3. harmoniske. Dette er vist på figur 11.13.

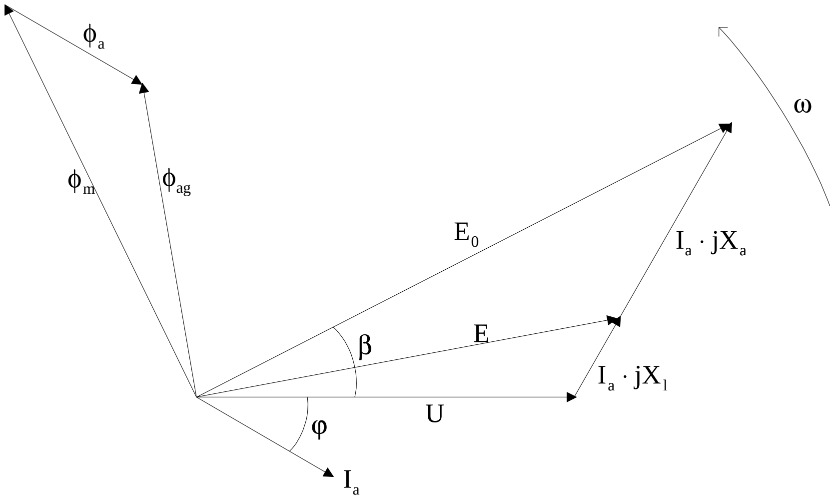


Figur 11.13: Fasespenninger og linjespenning for stjernekoblede spoler med skrittforkorting og fasedreide tørm

Ved hjelp av disse metodene kan en eliminere det aller meste av overharmoniske spenningskomponenter, selv ved en nokså ujevn fluksfordeling i luftgapet.

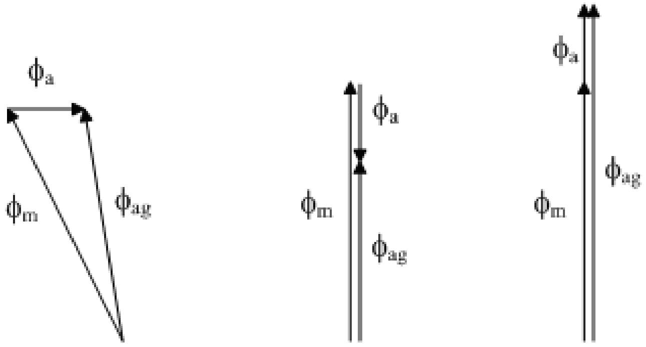
11.5 Ankerreaksjon

Ved tomgang vil luftgapsfeltet kun være bestemt av rotorstrømmen. Når maskinen belastes, vil det gå en ankerstrøm (statorstrøm) som skaper sitt eget felt. De to feltene, polhjulsfeltet ϕ_m og ankerfeltet ϕ_a, vil vekselvirke, og dermed vil luftgapsfeltet ϕ_{ag} være vektorsummen av de to. Dette fremgår av figur 11.14. En kan her legge merke til at indusert spenning ved tomgang E_0 er forskjellig fra den faktiske induserte spenningen E. Dette skyldes selvsagt ankerfeltets innvirkning på hovedfeltet.



Figur 11.14: Synkronmaskinens felter, spenninger og ankerstrøm

Figur 11.15 viser hvordan de to feltene ligger i forhold til hverandre ved resistiv last (til venstre), induktiv last (i midten) og kapasitiv last (til høyre).

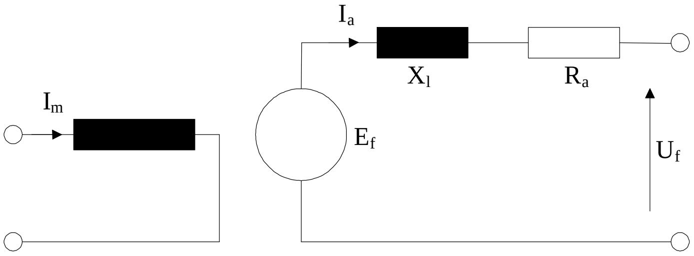


Figur 11.15: Ankerfeltets innvirkning på luftgapsfeltet (ankerreaksjonen)

Ved resistiv last vil ankerfeltet og hovedfeltet ligge mer eller mindre vinkelrett på hverandre, avhengig av hvor stor belastningen er. Ved rent induktiv last vil ankerfeltet motvirke hovedfeltet. Dette har stor betydning ved en kortslutning, hvor kortslutningsstrømmen, som hovedsakelig er induktiv, vil dempe luftgapsfeltet, og dermed også den induserte generatorspenningen. Dette forholdet gjør at kortslutningsstrømmen blir mye lavere enn den ellers ville ha vært. Ved kapasitiv last virker hovedfelt og ankerfelt i samme retning. Dette kan føre til dårlig stabilitet, for eksempel ved lange overføringslinjer med lav last.

11.6 Ekvivalentskjema

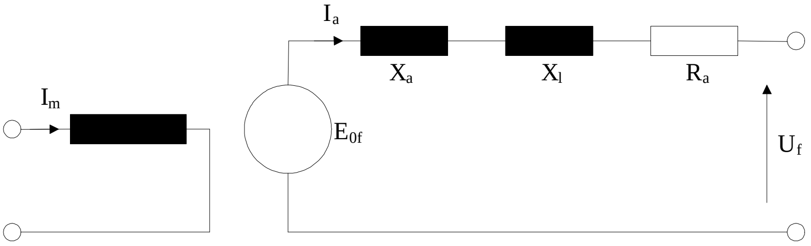
Figur 11.16 viser ekvivalentskjema per fase for en synkronmaskin. Til venstre på figuren vises rotorkretsen, hvor magnetiseringsstrømmen I_m påvirker indusert fasespenning E_f. Den påvirkes imidlertid også av ankerstrømmen I_a, på grunn av ankerreaksjonen. X_l er lekkreaktansen i statorviklingene, og R_a er resistansen i statorviklingene. U_f er nettspenningens faseverdi.



Figur 11.16: Ekvivalentskjema for synkronmaskin

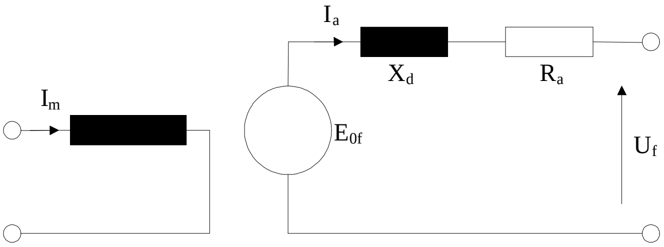
Den store ulempen med denne modellen er at spenningskilden E_f er avhengig av to størrelser, både I_m og I_a.

Figur 11.17 viser et alternativt ekvivalentskjema, hvor ankerreaksjonen er modellert i form av en ekstra reaktans X_a, og hvor spenningskilden er indusert fasespenning i tomgang E_{0f}, som kun er avhengig av magnetiseringsstrømmen I_m og ikke av ankerstrømmen I_a.



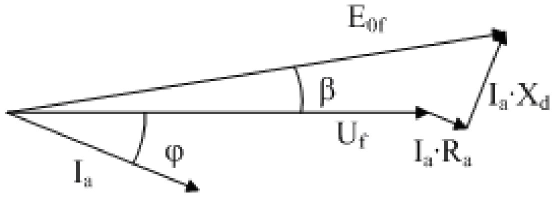
Figur 11.17: Ekvivalentskjema med ankerreaktans

Det er nærliggende å forenkle skjemaet på figur 11.17 ved å slå sammen de to reaktansene X_a og X_l til en resulterende synkronreaktans X_d. Dette er en teoretisk størrelse, men den danner en god modell av hvordan nettet "ser" synkronmaskinen ved stasjonær drift. Den består av en virkelig reaktans forårsaket av lekkfeltet i ankeret og av en tilsynelatende reaktans forårsaket av ankerreaksjonen. Figur 11.18 viser dette forenklede ekvivalentskjemaet.



Figur 11.18: Forenklet ekvivalentskjema med synkronreaktans

Figur 11.19 viser fasespenninger, ankerstrøm, samt fasevinkelen φ oglastvinkelen β. Sistnevnte viser vinkelen mellom tomgangsindusert spenning og nettspenning.



Figur 11.19: Viserdiagram for synkronmaskinens fasespenninger og -strømmer

Dette ekvivalentskjemaet gjelder kun for sylindriske rotorer. For rotorer med utpregede poler gjelder figur 11.18 for den komponenten av ankerstrømmen som er i fase med magnetpolenes langsgående akse (direct axis). Derav indeks d for synkronreaktansen. Den komponenten av ankerstrømmen som ligger på tvers av magnetpolene (quadrature axis) vil ”se” en synkronreaktans X_q som er forskjellig fra X_d. For sylindriske rotorer er $X_d = X_q$, og ett ekvivalentskjema kan benyttes. For enkelthelts skyld antas at $X_d = X_q$ også for rotorer med utpregede poler.

Eksempel 2 *En* $50\,\mathrm{MV\,A}$ *synkrongenerator er tilkoblet et* $10\,\mathrm{kV}$ *nett. Ankerresistansen* $R_a = 0,1\,\Omega$. *Lekkreaktansen* $X_l = 0,8\,\Omega$*, og ankerreaktansen* $X_a = 1,6\,\Omega$*. I et driftstilfelle er* $P = 30\,\mathrm{MW}$ *og* $Q = 20\,\mathrm{MV\,A}$*r ved en magnetiseringsstrøm* $I_m = 200\,\mathrm{A}$*. Beregn indusert fasespenning* E_f *og tomgangsindusert fasespenning* E_{0f}*. Beregn også tomgangsindusert fasespenning* E_{0f} *dersom rotorstrømmen endres til* $170\,\mathrm{A}$*. Se bort fra metning i jernet.*

Løsning:
Ankerstrøm:

$$I_a = \frac{P - jQ}{\sqrt{3}U} = \frac{(30 - j20)\cdot 10^6}{\sqrt{3}\cdot 10000} = 2,08\,\mathrm{kA}\angle - 33,7\,^\circ$$

Fasespenning:

$$U_f = \frac{10000}{\sqrt{3}} = 5,77\,\mathrm{kV}$$

Indusert fasespenning:

$$\overrightarrow{E}_f = U_f + \overrightarrow{I}_a \cdot (R_a + jX_l) = 5770 + 2080\angle - 33,7\,^\circ \cdot (0,1 + j0,8) = 6,98\,\mathrm{kV}\angle 10,5\,^\circ$$

Tomgangsindusert fasespenning:

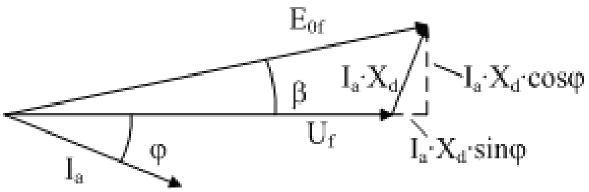
$$\overrightarrow{E}_{0f} = U_f + \overrightarrow{I}_a \cdot j\,(X_l + X_a) = 5770 + 2080\angle - 33,7\,^\circ \cdot (0,1 + j\,(0,8 + 1,6)) = 9.61\,\mathrm{kV}\angle 24,9\,^\circ$$

Ny verdi:

$$E_{0f} = 9,61 \cdot \frac{170}{200} = 8,17\,\mathrm{kV}$$

Siden viklingsresistansen R_a er mye mindre enn synkronreaktansen X_d, velger man ofte å se bort fra R_a. Viserdiagrammet på figur 11.20 er basert på denne forenklingen.
Det fremgår av figuren at det aktive spenningsfallet over synkronreaktansen (loddrett stiplet linje) kan uttrykkes ved

$$\mathrm{I_a X_d} \cos\varphi = \mathrm{E_{0f}} \sin\beta \tag{11.6}$$



Figur 11.20: Viserdiagram for synkronmaskin uten ankerresistans

Avgitt effekt fra maskinen vil være gitt ved

$$P = 3U_f I_a \cos\varphi \tag{11.7}$$

Hvis man setter (11.5) inn i (11.7), blir resultatet

$$P = 3U_f I_a \cos\varphi = 3U_f \frac{E_{0f}\sin\beta}{X_d \cos\varphi}\cos\varphi = 3\frac{E_{0f}U_f}{X_d}\sin\beta \tag{11.8}$$

Formel (11.8) viser at avgitt effekt P er bestemt av lastvinkelen β når tomgangsindusert spenning og klemmespenning holdes konstant. Maksimal avgitt effekt vil samsvare med en lastvinkel på $90°$:

$$P_{max} = 3\frac{E_{0f}U_f}{X_d} \tag{11.9}$$

Det vil i praksis aldri være aktuelt å belaste en synkronmaskin så kraftig, da den vil være farlig nær marginene for stabil drift, og selv en liten forstyrrelse kan være nok til å slippe luftgapsfeltet. En maskin i motordrift vil i så fall stanse, og en generator vil ruse ut.
Tilsvarende er avgitt reaktiv effekt gitt ved

$$Q = 3\frac{U_f}{X_d}\left(E_{0f}\cos\beta - U_f\right) \tag{11.10}$$

Formel (11.8) og (11.10) kan også uttrykkes med hensyn på linjespenningene:

$$P = \frac{E_0 U}{X_d}\sin\beta \tag{11.11}$$

$$Q = \frac{U}{X_d}\left(E_0\cos\beta - U\right) \tag{11.12}$$

Eksempel 3 *En* 4*-polig synkronmaskin med sylindrisk rotor og neglisjerbare tap står tilkoblet et* 50 *Hz trefasenett med konstant spenning* 380 *V. Synkronreaktansen er* $10\,\Omega$ *per fase, og tomgangsindusert spenning* $E_{0f} = 25 \cdot I_m$*. Hvor mye reaktiv effekt vil maskinen avgi eller motta når* $I_m = 10$ *A og maskinen går i aktiv tomgang? Hvor stort lastmoment kan maskinen ha ved en magnetiseringsstrøm på* 10 *A?*

Løsning:
Tomgangsndusert spenning er

$$E_0 = \sqrt{3} \cdot 25 \cdot I_m = \sqrt{3} \cdot 25 \cdot 10 = 433\,\mathrm{V}$$

Reaktiv effekt:

$$Q = \frac{U}{X_d}\left(E_0 \cos\beta - U\right) = \frac{380}{10}\left(433 \cos 0\,^\circ - 380\right) = 2,01\mathrm{kVAr}$$

Maksimal overførbar aktiv effekt (ved $\beta = 90\,^\circ$):

$$P_{\max} = \frac{E_0 U}{X_d} = \frac{433 \cdot 380}{10} = 16,5\,\mathrm{kW}$$

En 4-polig maskin vil ha følgende vinkelhastighet:

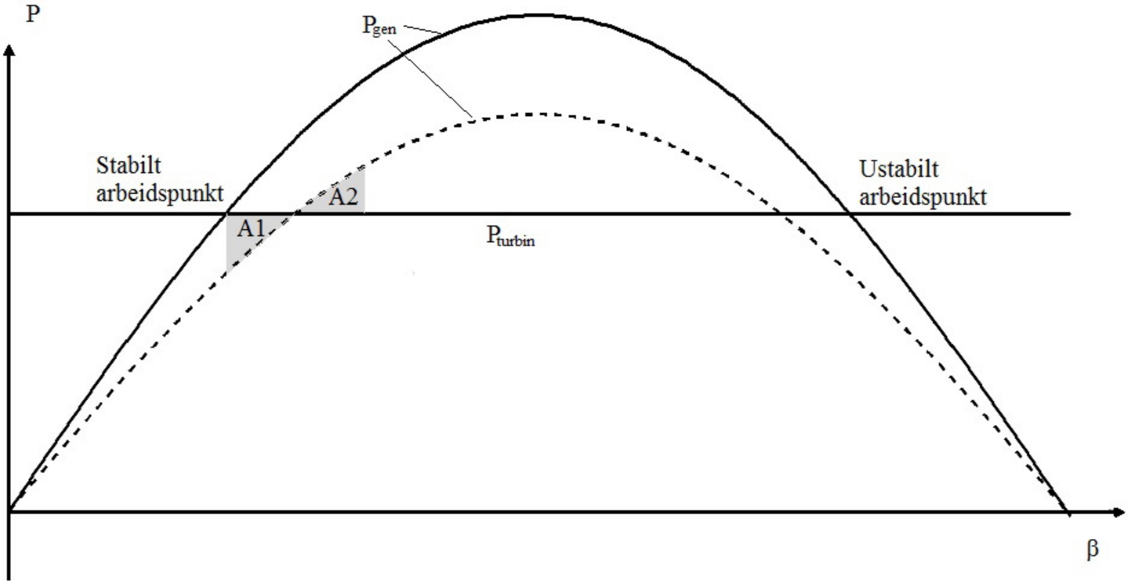
$$\omega_s = \frac{2\pi f}{p} = \frac{2\pi \cdot 50}{2} = 157\,\mathrm{rad/\,s}$$

Maksimalt moment på akselen blir da

$$\mathrm{T_{max}} = \frac{\mathrm{P_{max}}}{\omega_\mathrm{s}} = \frac{16500}{157} = 105\mathrm{Nm}$$

11.7 Stasjonær og transient stabilitet

Formel (11.11) forteller at generatoreffekten, og dermed også generatorens bremsemoment, er avhengig av generatorspenningen, synkronreaktansen og lastvinkelen.
Figur 11.21 viser sammenhengen mellom turbineffekt og generatoreffekt. Heltrukket linje viser generatoreffekten ved normal spenning, mens stiplet linje viser effekten ved et spenningsfall. Turbineffekten vil være konstant og uavhengig av polhjulsvinkelen.
Det stabile arbeidspunktet vil være det venstre skjæringspunktet mellom turbineffekt og generatoreffekt. Skulle vinkelen øke, vil generatorens bremsemoment også øke, og polhjulet dras tilbake til riktig vinkel. Tilsvarende, hvis lastvinkelen avtar, vil turbinmomentet være større enn bremsemomentet, og polhjulet inntar stabil lastvinkel på ny. En ser av formel (11.11) at et spenningsfall eller en økning av reaktansen vil føre til at generatorens bremsemoment faller. Dette kan skje ved at nettspenningen plutselig faller eller at en av to parallelle tilkoblingslinjer faller ut. I så fall vil generatoreffekten falle fra den heltrukne linja til den stiplede linja.
Dersom spenningen plutselig faller, vil generatoren flytte seg til et nytt stabilt arbeidspunkt (skjæringspunktet mellom den vanrette linja og den stiplede). Arealet A1 representerer en akselerasjon av maskinen. Den vil derfor svinge helt til høyre kant av arealet A2 før den svinger tilbake mot det stabile arbeidspunktet. Arealet A2 representerer en oppbremsing av maskinen. Siden A1 og A2 er uttrykk for samme mekaniske energi, vil de være like store.
Dersom polhjulet svinger så langt at lastvinkelen passerer høyre skjæringspunkt mellom turbin- og generatoreffekt, vil maskinen miste stabilitet og vil ruse ut. Dette skjæringspunktet er et ustabilt arbeidspunkt.

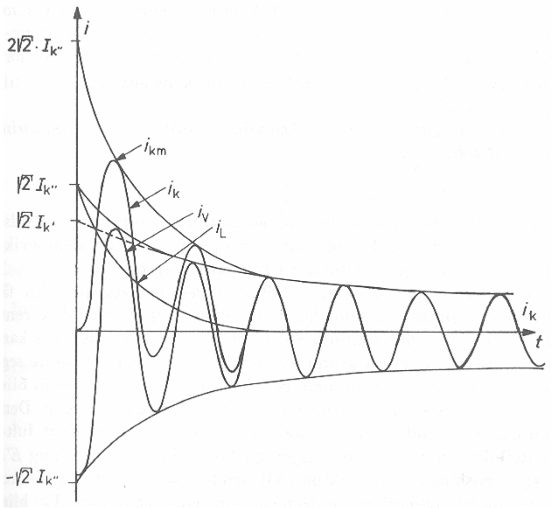


Figur 11.21: Turbin- og generatoreffekt som funksjon av lastvinkel

I virkeligheten er den transiente stabiliteten noe høyere enn likearealskriteriet skulle tilsi. Dette skyldes dempeviklingene, som sørger for at rotorutslaget blir noe mindre og som raskt bringer polhjulet tilbake til stabil drift. For å gi maskinen enda bedre demping, er det vanlig å koble en såkalt dempetilsats inn i feltkretsen. Dersom polhjulet går fortere enn synkron vinkelhastighet, økes indusert spenning, og dermed økes også bremsemomentet. Tilsvarende senkes indusert spenning hvis polhjulet går undersynkront.

11.8 Kortslutning

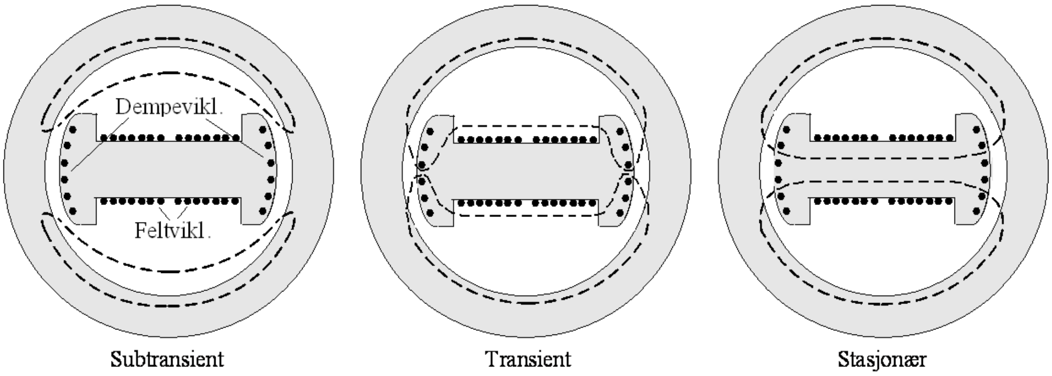
Dersom en kortslutning inntreffer på eller nær klemmene på maskinen, vil det oppstå kraftige kortslutningsstrømmer, som vist på figur 11.22. Det fremgår av figuren at strømmene først er meget kraftige, men avtar raskt til et mellomnivå og til slutt stabiliserer seg på en stasjonær verdi. De tre fasene kalles subtransient, transient og stasjonær kortslutningsstrøm.



Figur 11.22: Synkronmaskinens kortslutningsstrømmer

En legger også merke til at den subtransiente kortslutningsstrømmen noen ganger inneholder et likestrømsledd, avhengig av hvor i nettperioden feilen inntreffer. Siden kretsen er overveiende induktiv, kan ikke ankerstrømmene endre seg momentant, og dersom kortslutningen inntreffer ved spenningsmaksimum, vil likestrømsforskyvningen bli svært stor. Etter noen få nettperioder vil imdlertid vekselstrømmen igjen være balansert.

Figur 11.23 viser hvordan ankerfluksen endrer seg fra subtransient, via transient og til stasjonær kortslutningsstrøm. Idet kortslutningen inntreffer, vil hele ankerfluksen gå gjennom luft, fordi det tar lenger tid å bygge opp en fluks i jern. Et stort luftgap gir liten reaktans, og dermed høy kortslutningsstrøm. Dette skjer i den subtransiente perioden. Etter hvert vil fluksen finne vei gjennom rotorens dempeviklinger, og reaktansen vil øke noe. Den transiente kortslutningsstrømmen er derfor lavere enn den subtransiente. Til slutt vil ankerfluksen ha funnet sin vanlige vei gjennom jernet i både rotor og stator, og kortslutningsstrømmen møter en relativt høy stasjonær synkronreaktans. Derfor vil den stasjonære kortslutningsstrømmen bare være noen få ganger høyere enn maskinens merkestrøm. Dette er noe man bør ta hensyn til ved dimensjonering av vern for nødstrømsaggregat. Det kan være vanskelig å oppnå god selektivitet på grunn av det lave kortslutningsforholdet.



Figur 11.23: Ankerfluksens forløp gjennom kortslutning i synkronmaskin

11.9 Innfasing

Hvis man kobler en synkronmaskin direkte til trefasenettet, vil den ikke starte. Luftgapsfeltet vil rotere med synkront turtall, mens rotor på grunn av det høye treghetsmomentet ikke klarer å rotere med, men bare blir stående og dure. Dersom man benytter en frekvensomformer mellom maskin og nett, kan man øke nettfrekvensen langsomt, slik at rotor klarer å holde følge med luftgapsfeltet.

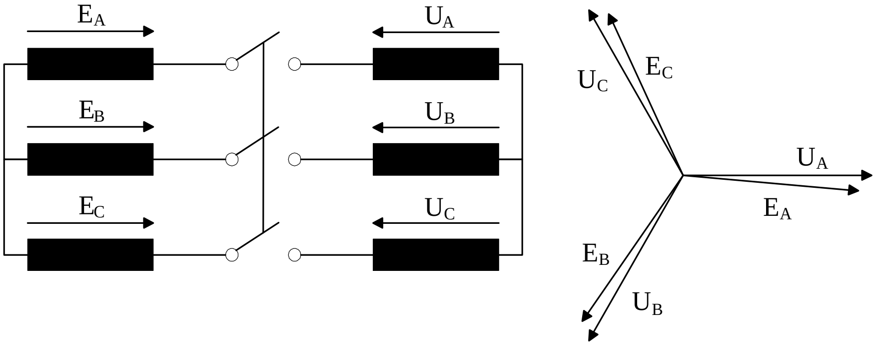
Bruker man en direktekoblet maskin, kreves en turbin eller en drivmotor som drar synkronmaskinen opp i synkront turtall. Deretter er det fire betingelser som må være oppfylt før maskinen kan kobles til nettet.

For det første må maskin og nett ha samme fasefølge. Dersom fasefølgen er ombyttet, vil ankerfelt og rotor gå i motsatt retning. Fasefølgen kontrolleres naturligvis bare en gang, nemlig ved montering av maskinen.

For det andre må maskin og nett ha samme spenning. Dersom spenningsnivået er ulikt, vil det oppstå et strømstøt ved innkoblingen, og hvis nivåforskjellen er stor nok, kan det flyte en uforholdsmessig høy ankerstrøm mellom maskin og nett. Se figur 11.24. Dersom betingelsen var oppfylt, skulle spenningsviserne på figuren vært like lange.

Denne betingelsen kontrolleres ved at man har voltmetre på begge sider av effektbryteren. Magnetiseringsstrømmen justeres til maskinspenningen er lik nettspenningen. Et voltmeter over en av bryterpolene vil vise spenningsforskjellen mellom maskin- og nettsiden av bryteren.

For det tredje må samsvarende spenninger være i fase. På figur 11.24 ser en at det er en fasedreining på noen grader, og det vil gi et strømstøt over bryteren ved innkobling, samt et ”rykk” i maskinen. Denne betingelsen kontrolleres enten med et synkronoskop eller med faselamper. Et synkronoskop er en trefase sleperingsmaskin hvor den ene siden er koblet til rotor og den andre siden til stator. Når

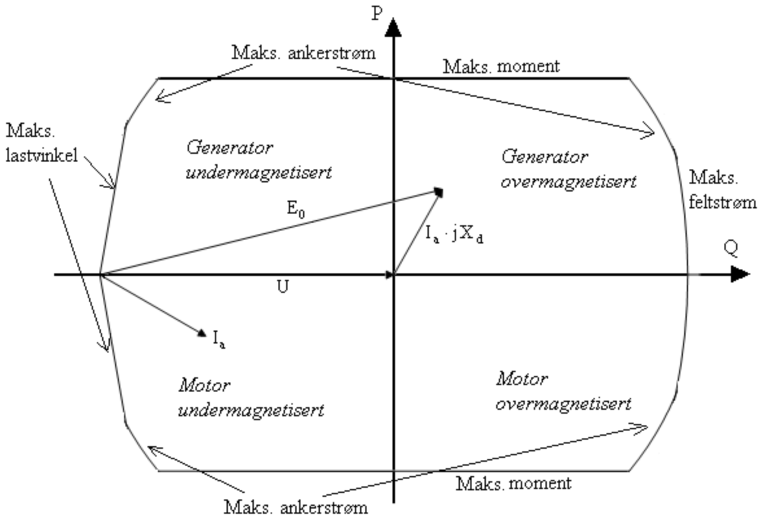


Figur 11.24: Spenningsforhold ved innfasing av synkronmaskin

nett og maskin er i fase, vil synkronoskopets rotor stå i en spesiell posisjon som er merket med en viser. Faselampene er koblet slik at de roterer eller blinker i et spesielt mønster, og når spenningene er i fase, vil enten alle tre være slukket (mørk innfasing), eller en lyser og de to andre er slukket (lys innfasing). Et voltmeter over en bryterpol vil også vise om spenningene er i fase eller ikke.
Den fjerde betingelsen er at maskin og nett har samme frekvens, og dermed samme synkrone vinkelhastighet. Dersom en kobler inn en maskin som går under- eller oversynkront, og de andre betingelsene er oppfylt, kan maskinens treghetsmoment være så stort at den ikke klarer å følge nettet, men kipper. Dessuten vil maskinen ha et driv- eller bremsemoment som kan føre til høye ankerstrømmer.

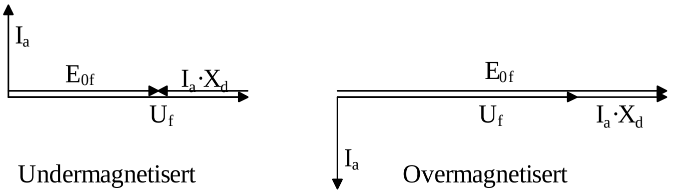
11.10 Driftsformer og V-kurver

Når maskinen er koblet til nettet, kan man variere både akselmoment og magnetisering for å oppnå de driftsforhold man måtte ønske. Figur 11.25 viser de ulike driftsmåtene. I tillegg kommer en vanlig driftsform, nemlig drift i aktiv tomgang, hvor maskinen enten er over- eller undermagnetisert. Maskinen vil da verken bruke eller levere aktiv effekt, men vil fungere som fasekompensator gjennom å bruke eller levere reaktiv effekt. Figur 11.25 viser også maskinens fysiske begrensninger, nemlig maksimal ankerstrøm, maksimal feltstrøm, maksimalt dreiemoment, samt grense for stabil lastvinkel.



Figur 11.25: Synkronmaskinens begrensninger og ulike driftsformer

Figur 11.26 viser spenningsvektorene ved aktiv tomgang. Dersom maskinen er undermagnetisert og man gradvis øker magnetiseringsstrømmen, vil ankerstrømmen avta lineært mot null, for så å øke igjen i motfase. Maskinen går over fra å trekke reaktiv effekt til å avgi reaktiv effekt. Det vil være en liten aktiv strømkomponent som medgår til aktive tap i maskinen, men ankerstrømmen er i hovedsak reaktiv.



Figur 11.26: Viserdiagrammer ved aktiv tomgang (fasekompensering)

Eksempel 4 *En synkronmaskin brukes som fasekompensator (aktiv tomgang). Maskinen er tilkoblet et* $10\,\mathrm{kV}$ *nett. Maskinen har en synkronreaktans* $X_d = 10\,\Omega$*. Hvilken indusert spenning må maskinen ha for å levere* $10\,\mathrm{MV\,A}$*r reaktiv effekt ut på nettet?*

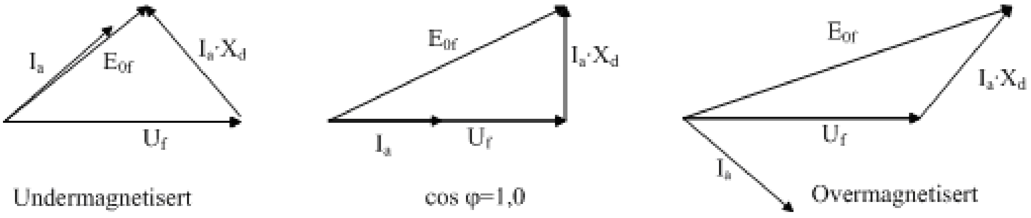
Løsning:
Siden lastvinkelen $\beta = 0$, blir uttrykket for reaktiv effekt

$$Q = \frac{U}{X_d}\left(E_0 \cos\beta - U\right) = \frac{U}{X_d}\left(E_0 - U\right)$$

Dette løses med hensyn på indusert spenning:

$$E_0 = Q\frac{X_d}{U} + U = 10 \cdot 10^6 \cdot \frac{10}{10000} + 10000 = 20\,\mathrm{kV}$$

Figur 11.27 viser ankerstrøm og spenninger ved halv last. Hvis man øker fra under- til overmagnetisering, vil ankerstrømmen endres mer gradvis, og minimumspunktet vil være ved $\cos\varphi = 1,0$. Sammenligner man figur 11.26 og 11.27, ser man at overgangen fra under- til overmagnetisering skjer ved en høyere magnetisering ved halv last enn ved tomgang.



Figur 11.27: Viserdiagrammer ved halv last

Eksempel 5 *En synkronmaskin tilkoblet et* $10\,\mathrm{kV}$ *nett med en synkronreaktans* $X_d = 7,5\,\Omega$ *leverer* $8,0\,\mathrm{MW}$ *ved en indusert spenning* $E_0 = 12\,\mathrm{kV}$*. Beregn maskinens lastvinkel, samt reaktiv effektflyt. Er maskinen over- eller undermagnetisert?*

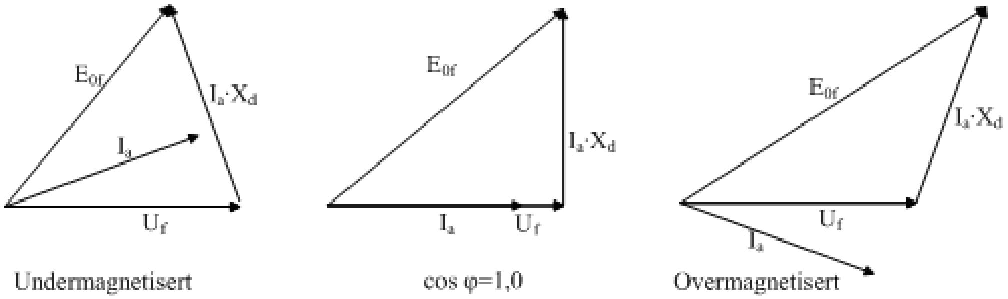
Løsning:
Lastvinkelen er

$$\beta = \arcsin\left(\frac{PX_d}{E_0 U}\right) = \arcsin\left(\frac{8,0 \cdot 10^6 \cdot 7,5}{12000 \cdot 10000}\right) = 30\,^\circ$$

Reaktiv effektflyt er

$$Q = \frac{U}{X_d}\left(E_0 \cos\beta - U\right) = \frac{10000}{7,5}\left(12000 \cos 30\,^\circ - 10000\right) = 523\,\mathrm{kV\,Ar}$$

Siden Q er positiv, leverer maskinen reaktiv effekt til nettet og er altså overmagnetisert.
Figur 11.28 viser forholdene ved full last. En ser at ankerstrømmen er høy og endrer seg lite om en endrer magnetiseringen. Den aktive strømkomponenten er den dominerende, noe som gjenspeiler seg i at fasevinkelen mellom strøm og spenning er moderat.



Figur 11.28: Viserdiagrammer ved full last

Eksempel 6 *En synkronmaskin er tilkoblet et* $15\,\mathrm{kV}$ *nett gjennom en svak nettforbindelse (total synkronreaktans* $X_d = 12\,\Omega$*). For å utnytte kapasiteten best mulig, kjøres maskinen med* $\cos\varphi = 1,0$*. Maskinen drives med en indusert spenning* $E_0 = 25\,\mathrm{kV}$*. Regn ut lastvinkel og aktiv effektproduksjon.*

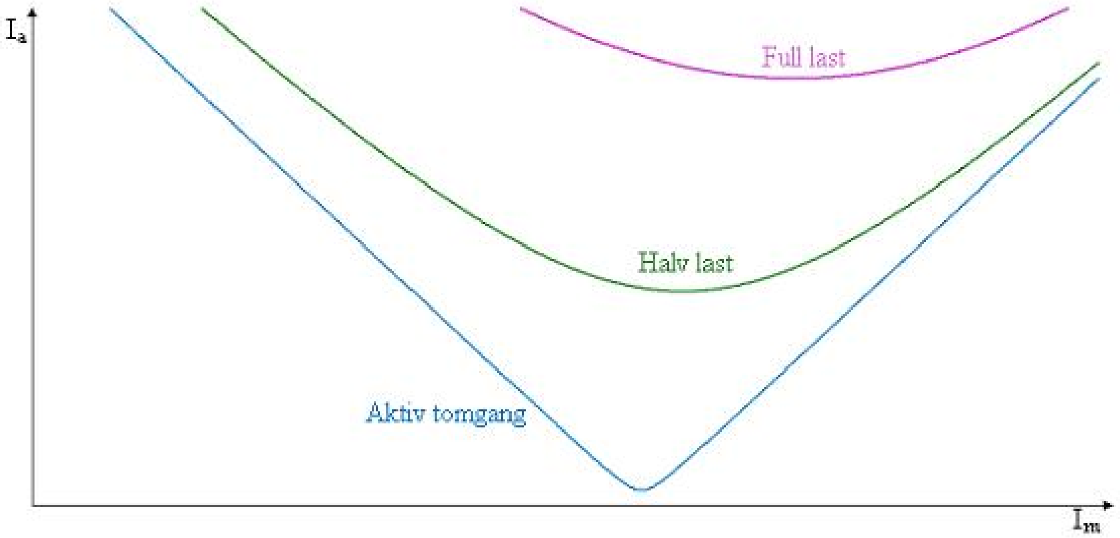
Løsning:
Ved $\cos\varphi = 1,0$ er $Q = 0$. Dette gir at

$$\begin{aligned}\frac{U}{X_d}\left(E_0 \cos\beta - U\right) &= 0\\ \frac{E_0 U}{X_d}\cos\beta &= \frac{U^2}{X_d}\\ \beta &= \arccos\left(\frac{U}{E_0}\right) = \arccos\left(\frac{15}{25}\right) = 53,1\,^\circ\end{aligned}$$

Aktiv effektproduksjon blir dermed

$$P = \frac{E_0 U}{X_d}\sin\beta = \frac{25000 \cdot 15000}{12}\sin 53,1\,^\circ = 25\,\mathrm{MW}$$

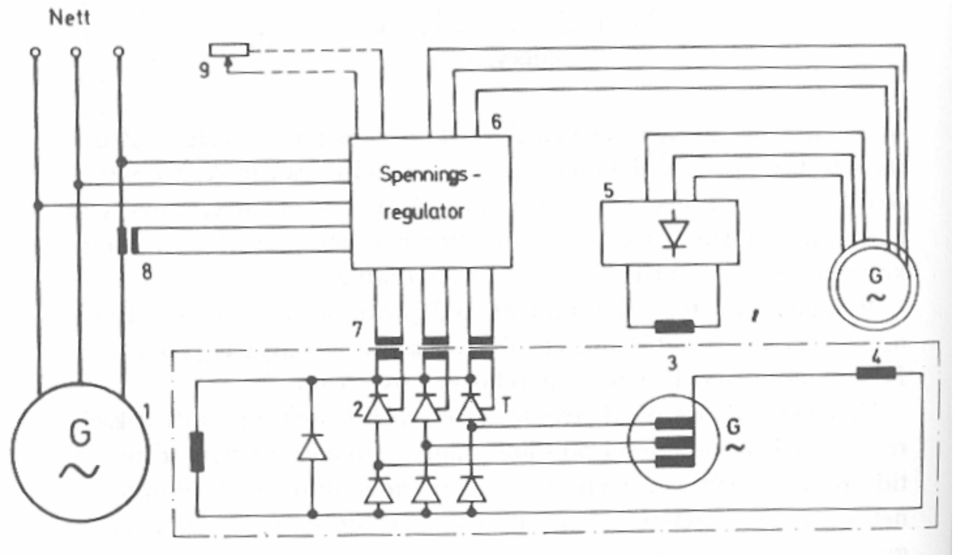
Figur 11.29 viser ankerstrømmen som en funksjon av magnetiseringsstrømmen for ulik grad av mekanisk last på akselen. En ser at ankerstrømmen danner kurver med en slags V-form. Grunnen er at ankerstrømmen øker både ved under- og overmagnetisering, noe som også fremkommer av figurene 11.26 – 11.28.



Figur 11.29: Synkronmaskinens V-kurver

11.11 Børsteløs magnetisering

En av ulempene med synkronmaskinen er at den er avhengig av børster og sleperinger for å få magnetisert rotor. For synkronmaskiner av moderat størrelse, er det imidlertid mulig å magnetisere rotor uten børster og sleperinger. Figur 11.30 viser et slikt system. Alt som befinner seg innenfor den stiplede linjen, befinner seg på rotorakselen. Diodelikeretteren (5) leverer strøm til en stillestående feltvikling på stator (3). Denne forsyner en halvstyrt bro (2). Tyristorene mottar tennpulser via pulstransformatorene (7) og leverer en styrt likestrøm til hovedgeneratorens feltvikling (1).

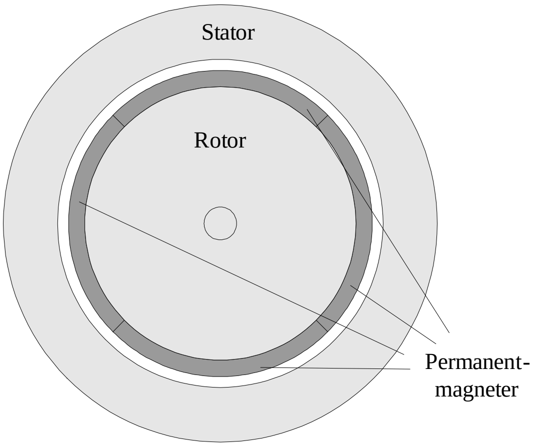


Figur 11.30: System for børsteløs magnetisering av synkrongeneratorer

Det finnes flere ulike utgave av børsteløs magnetisering, men felles for dem alle er at de er utstyrt med en likeretter på rotorakselen.

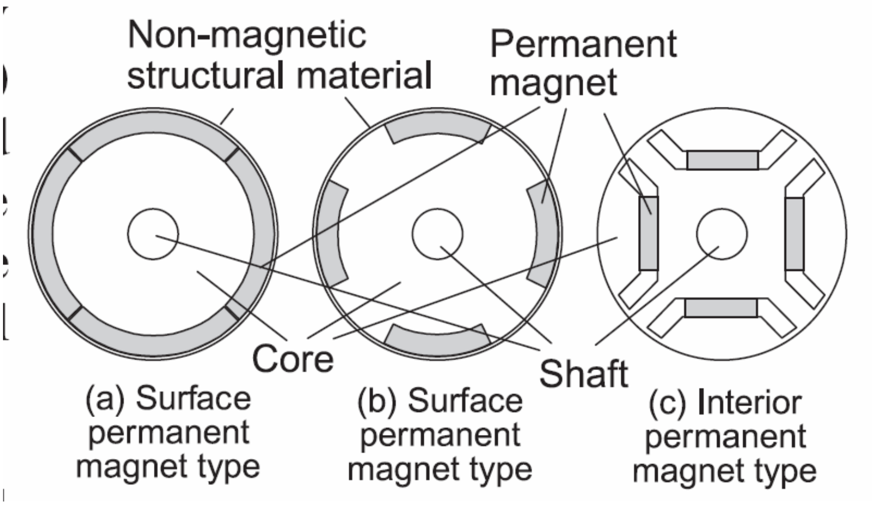
11.12 Permanentmagnet synkronmaskiner

En annen måte å unngå sleperinger, er å utstyre rotoren med permanentmagneter. For mindre motordrifter har denne løsningen fått større utbredelse i de senere år, ikke minst på grunn av nye og bedre permanentmagneter. En synkronmaskin med permanentmagneter er like robust som en burviklet asynkronmaskin. Figur 11.31 viser en prinsippskisse av en permanentmagnet synkronmotor.



Figur 11.31: Prinsippskisse av permanentmagnet synkronmotor

Det fins flere ulike måter å konstruere rotor på. Figur 11.32 viser de vanligste. Til venstre på figuren vises et system med overflatemonterte magneter som dekker hele omkretsen. Dette gir en ganske firkantet fluksfordeling. I midten ses en løsning hvor magnetene er nedfelt i jernet, noe som gir en mer trapesformet fluks. Til høyre vises et system der magnetene er innebygget i jernet, og dette gir den beste fluksfordelingen, men også den mest kompliserte konstruksjonen. Ved bruk av overflatemonterte magneter legges et umagnetisk lag ytterst på rotor for å beskytte magnetene og holde dem på plass.



Figur 11.32: Ulike utførelser av rotor med permanentmagneter

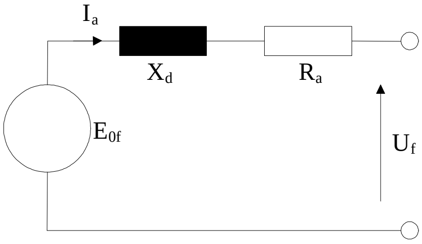
Når en benytter permanentmagneter i rotor, kan en ikke regulere hovedfeltet, bare ankerfeltet. I tomgang vil indusert spenning være proporsjonal med frekvensen:

$$\begin{gathered} E_{0f} = 4,44 \cdot N_{eff} \cdot f \cdot \phi_{\max} \\ E_{0f} = k_1 \cdot f \end{gathered} \tag{11.13}$$

Dermed vil indusert spenning også være proporsjonal med turtallet:

$$E_{0f} = k_2 \cdot n \tag{11.14}$$

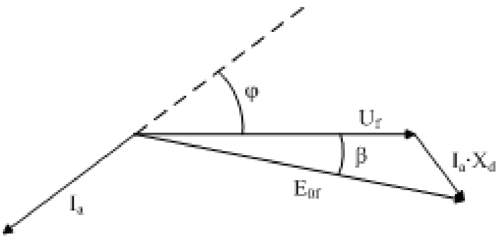
Ekvivalentskjemaet vil se ut som på figur 11.33, og en legger merke til at det ikke er noen magnetiseringskrets, i motsetning til ekvivalentskjemaet på figur 11.18.



Figur 11.33: Ekvivalentskjema for permanentmagnet synkronmaskin

Eksempel 7 *En* $2,0$ *kW* 4*-polig permanentmagnet synkronmotor har en merkespenning på* 230 *V ved en frekvens på* 50 *Hz. Ved merkedrift leverer den reaktiv effekt til nettet med en effektfaktor* $\cos\varphi = 0,8$*. Ankerresistansen er neglisjerbar, og synkronreaktansen er* $8,0\,\Omega$ *per fase. Beregn ankerstrømmen ved merkedrift. Hva blir turtallet og indusert tomgangsspenning ved merkefrekvens? Hva blir indusert tomgangsspenning og ankerstrøm ved et turtall på* 900 *o/min dersom drivmomentet er uendret og klemmespenningen er* 140 *V? Hva blir frekvensen da?*

Løsning:
Vi tar utgangspunkt i figur 11.33. Siden dette er et ekvivalentskjema for generatordrift, må ankerstrømmen snus $180°$ ved motordrift, slik det er vist på nedenstående figur. At motoren leverer reaktiv effekt, betyr at strømmen ligger foran spenningen, og motoren er overmagnetisert. Dette ser en gjennom at tomgangsindusert spenning har en større x-komponent enn klemmespenningen.



Tilsynelatende effekt ved merkedrift blir

$$S_N = \frac{P_N}{\cos\varphi} = \sqrt{3}U_N I_N$$

Ankerstrømmen blir da

$$I_{aN} = \frac{P_N}{\sqrt{3}U_N\cos\varphi} = \frac{2000}{\sqrt{3}230 \cdot 0,8} = 6,28\,\mathrm{A}$$

Turtallet ved merkedrift er

$$n_N = \frac{60 \cdot f_N}{p} = \frac{60 \cdot 50}{2} = 1500 \text{ o/min}$$

Den aktive (loddrette) delen av ankerspenningsfallet blir

$$I_{aN}X_d\cos\varphi = 6,28 \cdot 8,0 \cdot 0,8 = 40,2\,\mathrm{V}$$

Den reaktive (vannrette) delen av ankerspenningsfallet blir

$$I_{aN}X_d\sin\varphi = 6,28 \cdot 8,0 \cdot 0,6 = 30,1\,\mathrm{V}$$

Tomgangsindusert spenning blir

$$E_{0fN} = \sqrt{\left(I_{aN}X_d\cos\varphi\right)^2 + \left(U_{fN} + I_{aN}X_d\sin\varphi\right)^2} = \sqrt{40,2^2 + \left(\frac{230}{\sqrt{3}} + 30,1\right)^2} = 168\,\mathrm{V}$$

Drivmomentet ved merkedrift er

$$T_N = \frac{P}{\omega_N} = \frac{P}{\frac{2\pi f}{p}} = \frac{2000}{50\pi} = 12,7\,\mathrm{N\,m}$$

Avgitt effekt ved 900 o/min er

$$P = T_N \cdot \omega = T_N\frac{2\pi}{60}n = 12,7 \cdot \frac{2\pi}{60} \cdot 900 = 1,20\,\mathrm{kW}$$

Siden den aktive delen av ankerspenningsfallet er proporsjonal med effekten, får vi at

$$I_aX_d\cos\varphi = \frac{1,2}{2,0} \cdot 40,2 = 24,1\,\mathrm{V}$$

Indusert tomgangsspenning er

$$E_{0f} = \frac{1,2}{2,0} \cdot 168 = 101\,\mathrm{V}$$

Lastvinkelen er

$$\beta = \arcsin\left(\frac{I_aX_d\cos\varphi}{E_{0f}}\right) = \arcsin\left(\frac{24,1}{101}\right) = 13,8\,^\circ$$

Fasespenningen er

$$U_f = \frac{140}{\sqrt{3}} = 80,8\,\mathrm{V}$$

Vi bruker cosinussetningen til å finne ankerspenningsfallet:

$$I_aX_d = \sqrt{E_{0f}^2 + U_f^2 - 2 \cdot E_{0f} \cdot U_f \cdot \cos\beta} = \sqrt{101^2 + 80,8^2 - 2 \cdot 101 \cdot 80,8 \cdot \cos\left(13,8\,^\circ\right)} = 29,7\,\mathrm{V}$$

Ankerstrømmen blir da

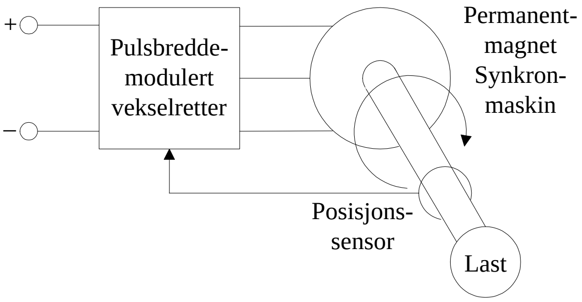
$$I_a = \frac{29,7}{8,0} = 3,71\,\mathrm{A}$$

Frekvensen blir

$$f = \frac{p}{60} \cdot n = \frac{2}{60} \cdot 900 = 30\,\mathrm{Hz}$$

11.13 Børsteløs likestrømsmotor (børsteløs DC)

Børsteløs likestrømsmotor er en fellesbetegnelse for motordrifter som mates med likestrøm, men hvor maskinen er en vekselstrømsmaskin uten børster. En kan da velge mellom permanentmagnet synkronmotorer (kapittel 11.12), reluktansmotorer (11.14) eller burviklede asynkronmotorer. Dersom ikke styresystemet har smart funksjonalitet som beregner hvor rotor befinner seg, må en posisjonssensor festes på motorakselen. Bøsteløs DC bruker altså alltid en vekselstrømsmaskin, men motordriften er tilkoblet et likestrømsnett eller en likestrømskilde, derav DC-betegnelsen.
Figur 11.34 viser omformersystemet for en børsteløs likestrømsmotor. Den prinsipielle oppbyggingen er den samme som for en frekvensstyring av en asynkronmaskin, og en kan benytte samme type omformere. Forskjellen ligger i selve styringen. Posisjonssensoren gir også informasjon om turtallet, og dermed kan man enkelt beregne indusert spenning i henhold til formel (11.13). Vekselretteren gir ut en variabel motorspenning og –frekvens og styres slik at ankerstrømmene har en gitt fasedreining i forhold til klemmespenningene. Dermed kan en kontrollere både drivmoment og felt i maskinen.



Figur 11.34: Børsteløs likestrømsmotor

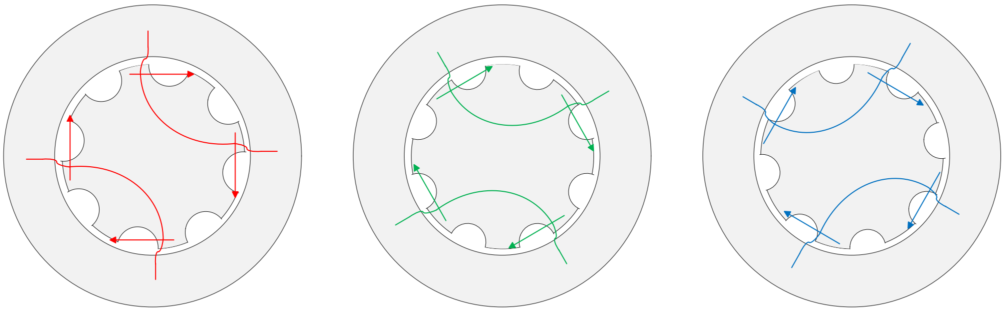
11.14 Reluktansmotor og trinnmotor

Reluktansmotor

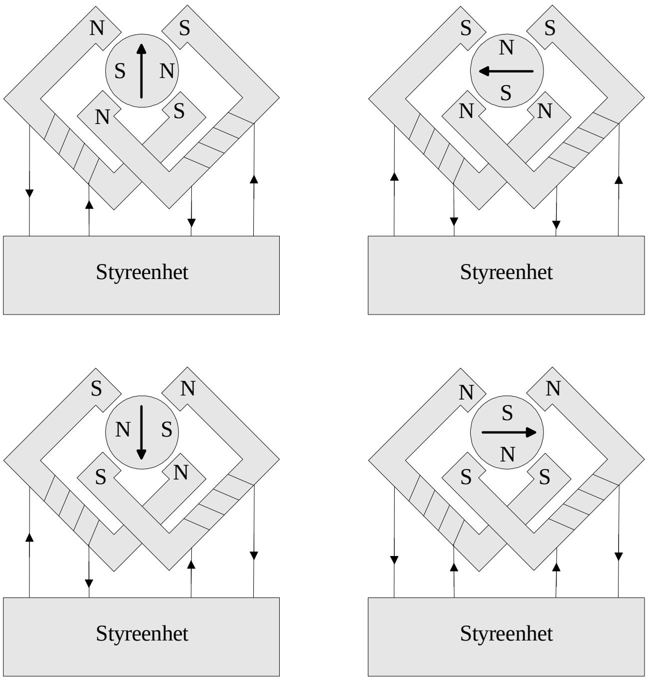
Reluktansmotoren på figur 11.35 har en rotor uten viklinger, men med en slags utpregede poler. Stator på figur 11.35 er viklet slik at den har to polpar. Til venstre på figuren går det strøm i fase U (markert med røde flukslinjer), og det oppstår en kraftvirkning markert med røde piler som gjør at rotor vrir seg med klokka. Deretter går det strøm i fase V (grønne flukslinjer), og kraftvirkningen markert med grønne piler skaper et moment som gjør at rotor vrir seg ytterligere. Dette er illustrert på den midterste figuren. Deretter går det strøm i fase W (blå flukslinjer), vist på figuren til høyre. Kraftvirkningen (blå piler) gjør at rotor dreier ytterligere. I dette eksemplet dreier rotor $15\,^\circ$ for hvert faseskift og $45\,^\circ$ i løpet av en periode. Strømretningen har ingen betydning. De tre faseviklingene er ikke koblet sammen, så maskinen krever seks tilkoblinger i stator. Den er også avhengig av en posisjonssensor for å koble inn riktig fase til riktig tid.

Trinnmotor

Trinnmotoren har to sett statorviklinger som er 90° faseforskjøvet, og en rotor med permanentmagnet. Figur 11.36 viser hvordan man ved å endre retningen på statorstrømmene kan bringe rotor i helt bestemte posisjoner. Styreenheten kontrollerer både hvilken posisjon rotor har, hvor mange omløp rotor foretar og hvor raskt rotor dreier rundt. Trinnmotoren (også kalt stegmotor eller stepmotor) brukes i systemer hvor det er behov for presis posisjonering, som for eksempel i antennestyringer og industriroboter.



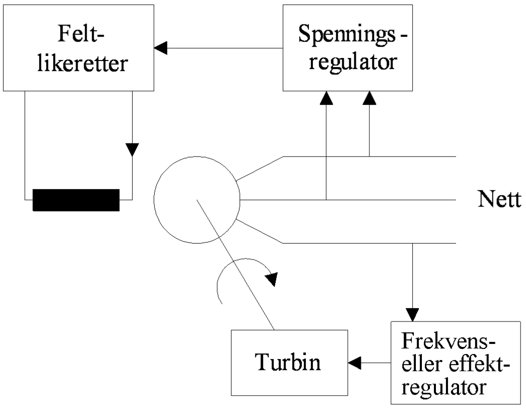
Figur 11.35: Prinsippskisse for reluktansmotor



Figur 11.36: Trinnmotor i ulike posisjoner

11.15 Frekvens-, effekt- og spenningsregulering av synkrongeneratorer

Figur 11.37 viser en nettilkoblet synkrongenerator med turbin- og feltregulator. Alle generatorene i samkjøringsnettet styres på denne måten. Dersom frekvensen i nettet synker, fordi den totale lasten i nettet øker, vil turbinregulatoren gi et økt pådrag på turbinventilen, og turbinmomentet øker. Dette skjer i en rekke store aggregat i nettet, og frekvensen vil vende tilbake til tilnærmet nominell verdi. En tilsvarende frekvensstigning vil føre til at turbinventilen reduserer turbinmomentet. Andre generatorer styres slik at de leverer konstant aktiv effekt ut på nettet.



Figur 11.37: Synkrongenerator med regulatorer

Dersom generatorspenningen faller, vil spenningsregulatoren øke magnetiseringen og på den måten holde nettspenningen oppe. En tilsvarende spenningsstigning fører til at magnetiseringen reduseres, og dermed bringes nettspenningen tilbake til sitt opprinnelige nivå.

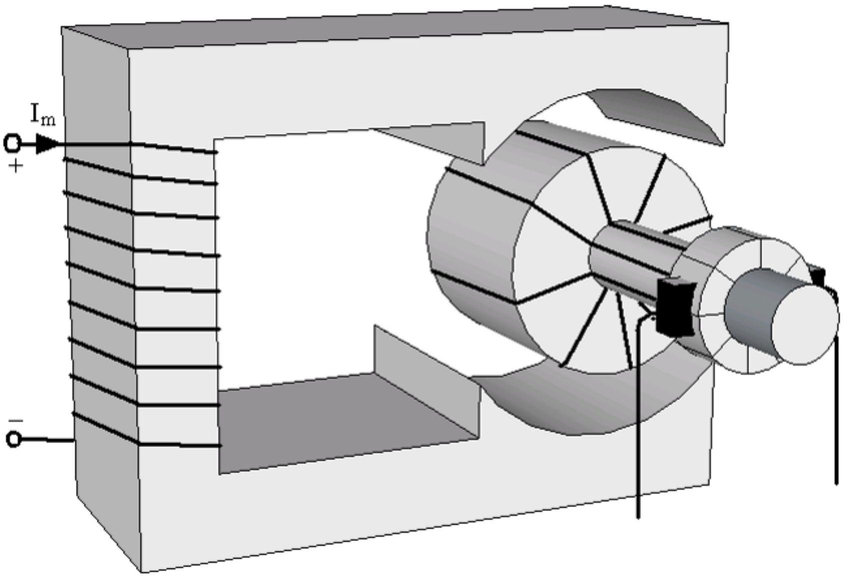
11.16 Øvingsoppgaver

1. Hvilke to rotortyper benyttes i synkronmaskiner?
2. Skisser luftgaps-mmk for rotor med utpregede poler med luftgapet langs x-aksen.
3. Luftgaps-mmk i oppgave 2 avviker mye fra sinusform. Hvilke tiltak kan gjøres for å gjøre generatorens klemmespenning mest mulig sinusformet?
4. Skisser polhjulsfluks, ankerfluks og resulterende luftgapsfluks på vektorform for induktiv last, kapasitiv last og resistiv last.
5. Hva er synkronreaktansen? Hvorfor er det vanlig å se bort fra ankerresistansen?
6. En synkronmaskin er tilkoblet et $8,0\,\mathrm{kV}$ nett. Ved en magnetiseringsstrøm på $150\,\mathrm{A}$ er indusert tomgangsspenning lik $15\,\mathrm{kV}$. Synkronreaktansen er $7,5\,\Omega$. Beregn avgitt aktiv og reaktiv effekt ved en lastvinkel lik $50\,^\circ$.
7. Hva blir reaktiv effekt dersom generatoren i oppgave 6 holder aktiv effekt konstant og magnetiseringsstrømmen økes til $180\,\mathrm{A}$? Se bort fra metning i jernet.
8. Hvilke tre faser gjennomgår en kortslutning på klemmene av en synkronmaskin? Hva er årsaken til disse ulike fasene?
9. Hvilke kriterier må være oppfylt før man kan koble en synkronmaskin inn på et spenningssatt trefasenett?
10. Skisser synkronmaskinens V-kurver for tomgang, halv last og full last.
11. En $20\,\mathrm{MVA}$ synkrongenerator med 5 polpar er tilkoblet et $10\,\mathrm{kV}$ stivt nett. Maksimal tomgangsindusert spenning er $18\,\mathrm{kV}$. Synkronreaktansen er $7,0\,\Omega$. I et driftstilfelle er turbinmomentet $350\,\mathrm{kNm}$. Er generatoren stasjonært stabil? Hva hender med en generator som mister stasjonær stabilitet?
12. Hvordan kan man magnetisere en viklet rotor uten å bruke sleperinger og børster?
13. Hva er børsteløs DC, og hvilke typer motorer egner seg best for dette formålet?
14. Hvordan styrer man aktiv effektproduksjon på en generator, og hvordan styrer man reaktiv effektproduksjon? Hvilken sammenheng er det mellom effekt og nettfrekvens? Hvilken sammenheng er det mellom effekt og nettspenning?

12 Kommutatormaskiner

12.1 Utførelse og virkemåte

Figur 12.1 viser en prinsippskisse av kommutatormaskinen. Feltviklingen til venstre på figuren skaper et stillestående felt i stator. Rotor er utstyrt med en ankervikling hvor hver vinding er koblet til en lamell på kommutatoren. Lamellene er innbyrdes isolert. To kullbørster ligger mot lamellene. Disse er koblet til en spenningskilde og sørger for at det til enhver tid går strøm gjennom de rotorlederne som befinner seg mellom magnetpolene. Dette skaper et drivmoment. Når neste sett med rotorledere befinner seg mellom magnetpolene, vil kommutatoren ha dreid rundt, slik at det er lamellene til disse lederne som befinner seg under børstene. Demed vil det til enhver tid være et sett strømførende rotorledere som befinner seg i feltet, og maskinen har konstant drivmoment.



Figur 12.1: Prinsippskisse for kommutatormaskin

Figur 12.2 viser en gjennomskåret kommutatormaskin. Til venstre ser en kommutatorene med børster som ligger mot lamellene. Til høyre ser en selve ankeret (rotor) med langsgående spor hvor rotorlederne er lagt ned. I motsetning til en synkronmaskin, er hovedstrømkretsen i rotor, og derfor kalles rotor for anker i en kommutatormaskin, mens stator inneholder feltviklinger. Ankeret vil ha et roterende felt (i forhold til rotorakselen), og rotorjernet må derfor bygges opp av isolerte blikkplater for å redusere jerntapene, mens statorjernet kan være massivt, siden statorfeltet er et likestrømsfelt.
Det vil induseres spenninger i rotorledere som beveger seg i et felt:

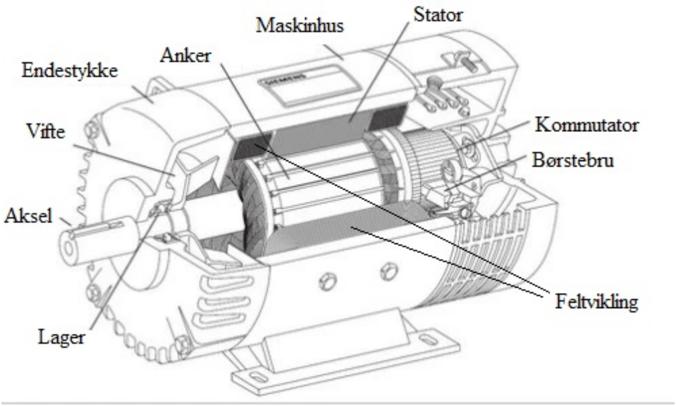
$$e = B \cdot \ell \cdot v \tag{12.1}$$

Siden den relative hastigheten v er proporsjonal med turtallet og flukstettheten er proporsjonal med fluksen, vil indusert spenning være avhengig av turtall og fluks:

$$E = k_E \cdot n \cdot \phi \tag{12.2}$$

hvor maskinkonstanten k_E vil være gitt for hver enkelt maskin.
Kraftvirkningen på en strømførende leder i et felt er

$$F = B \cdot i \cdot \ell \tag{12.3}$$

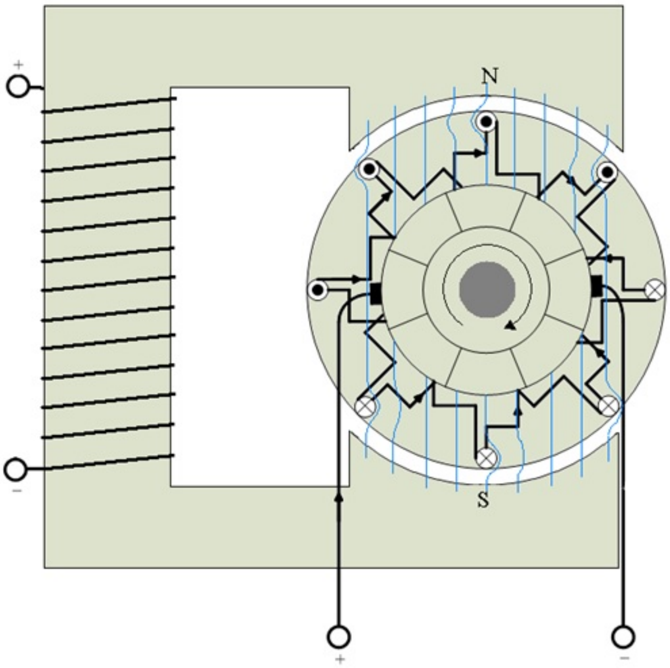


Figur 12.2: Gjennomskåret kommutatormaskin

Siden drivmomentet er proporsjonalt med kraftvirkningen på rotorlederne og flukstettheten er proporsjonal med fluksen, kan dreiemomentet uttrykkes som en funksjon av ankerstrøm og fluks:

$$T = k_T \phi I_a \tag{12.4}$$

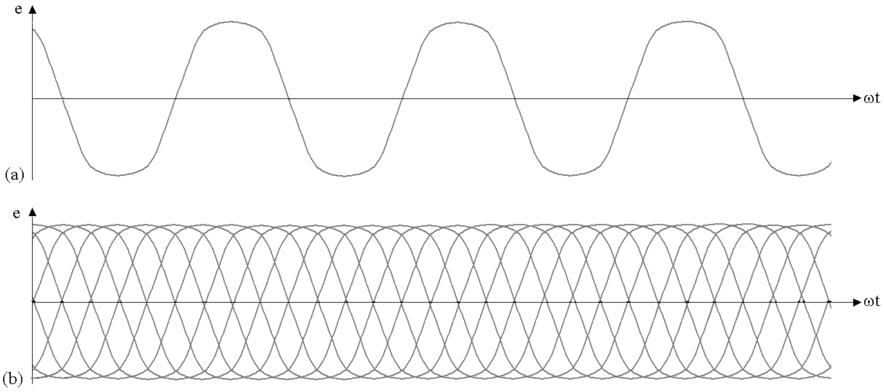
hvor k_T er en spesifikk maskinkonstant.



Figur 12.3: Momentutvikling i kommutatormaskin

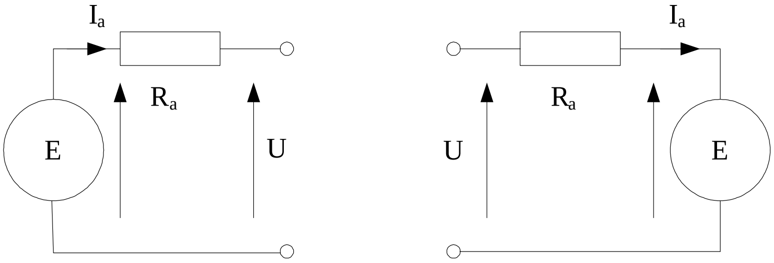
Figur 12.3 viser hvordan ankerstrømmene bøyer av hovedfeltet og dermed skaper ei kraftvirkning vikelrett på feltet. Under nordpolen virker kraften mor høyre, og under sydpolen virker den til venstre. De samlede kreftene bidrar til å skape dreiemoment i maskinen.

I hver rotorleder vil det induseres en vekselspenning, men på grunn av kommutatoren, vil klemmespenningen være likerettet og tilnærmet glatt. Dette fremgår av figur 12.4.



Figur 12.4: Indusert ankerspenning (a) i en enkelt leder, (b) over børstebrua

Figur 12.5 viser kommutatormaskinens ekvivalentskjema i generatordrift (til venstre) og motordrift (til høyre). Ved generatordrift vil indusert spenning E være større enn klemmespenningen U, og ankerstrømmen I_a flyter ut mot klemmene. Ved motordrift er E mindre enn U, og I_a går i motsatt retning.



Figur 12.5: Ekvivalentskjema for kommutatormaskin

Ved generatordrift vil det være følgende forhold mellom klemmespenning og indusert spenning:

$$U = E - I_a R_a \tag{12.5}$$

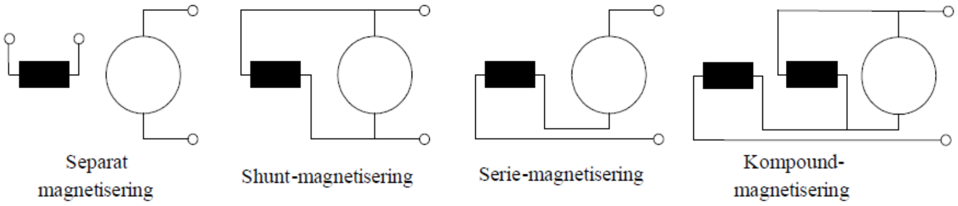
Ved motordrift blir forholdet:

$$U = E + I_a R_a \tag{12.6}$$

Ankerresistansen R_a innbefatter både resistans i ankerlederne og resistans i børstene.

12.2 Koblingsmåter

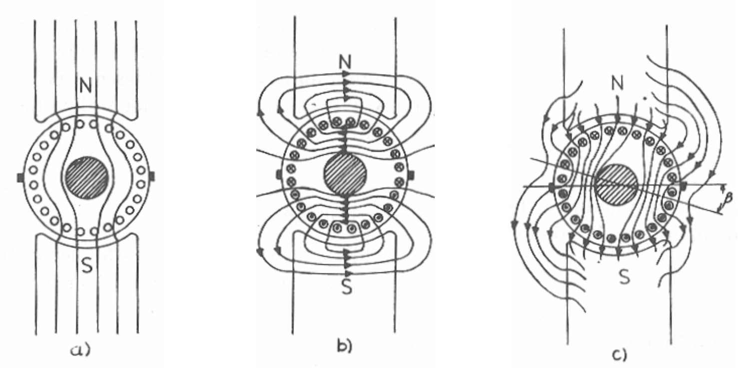
Som det fremgår av figur 12.1, har kommutatormaskinen to viklinger, ankerviklingen og feltviklingen. Disse kan være koblet på flere måter. Figur 12.6 viser de ulike koblingsmåtene. Ved separat magnetisering (fremmedmagnetisering) forsynes feltviklingen og ankeret fra separate spenningskilder. Ved shuntmagnetisering er viklingene koblet i parallell. Ved seriemagnetisering er de koblet i serie. Ved kompound-magnetisering brukes to feltviklinger, hvor den ene er koblet i serie og den andre i parallell med ankeret. En serievikling skal føre hele ankerstrømmen og består derfor av få tørn med stort tverrsnitt, mens en shuntvikling har mange tørn og lite tverrsnitt.



Figur 12.6: Ulike magnetiseringssystem for likestrømmaskiner

12.3 Ankerreaksjon

På samme måte som for synkronmaskinen, vil ankerfeltet i en kommutatormaskin vekselvirke med hovedfeltet. Figur 12.7 viser de ulike feltene. Figur 12.7a viser hovedfeltet, figur 12.7b viser ankerfeltet, og figur 12.7c viser det resulterende feltet som blir vridd en vinkel β på grunn av ankerreaksjonen. For å oppnå optimal drift, dreies børstebrua tilsvarende.



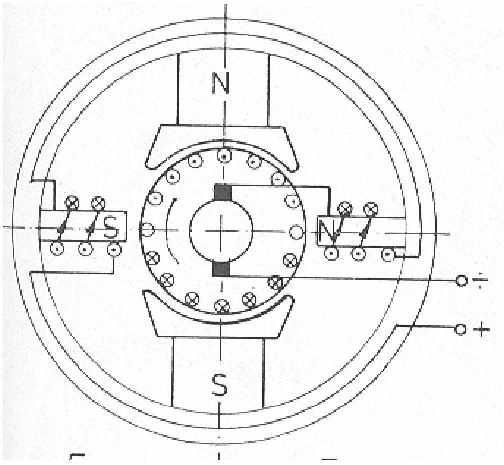
Figur 12.7: Ankerreaksjonen i en kommutatormaskin

En annen måte å motvirke ankerreaksjonen, er å montere et par vendepoler i stator, slik det er vist på figur 12.8. Disse polene fører hele ankerstrømmen og er viklet slik at de lager et felt som er like stort som ankerfeltet, men går i motsatt retning. Dermed opphever vendepolfeltet og ankerfeltet hverandre, og en unngår at hovedfeltet blir vridd, slik som på figur 12.7c.

12.4 Motorstyring

For en maskin med separat magnetisering eller shuntmagnetisering, kan en regne fluksen som konstant, og da blir drivmomentet proporsjonalt med ankerstrømmen:

$$T_{shunt} = k_1 I_a \tag{12.7}$$



Figur 12.8: Ankerkrets med vendepoler

For en seriemaskin vil fluksen være proporsjonal med ankerstrømmen, og da vil momentet være gitt ved:

$$T_{serie} = k_2 {I_a}^2 \tag{12.8}$$

Dersom en sammenfatter formel (12.2) og (12.6), får en at turtallet kan uttrykkes ved

$$n = \frac{E}{k_E \phi} = \frac{U - I_a R_a}{k_E \phi} \tag{12.9}$$

Turtallet for en shuntmotor blir

$$n_{shunt} = k_3 \left(U - I_a R_a\right) \tag{12.10}$$

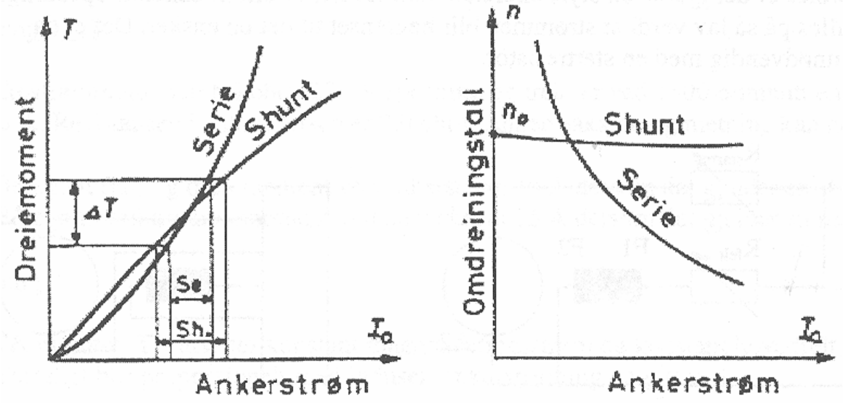
Turtallet for en seriemotor blir

$$n_{serie} = k_4 \frac{\left(U - I_a R_a\right)}{I_a} \tag{12.11}$$

For en shuntmotor vil feltet, og dermed også nevneren, være konstant. Turtallet vil være nokså konstant, med et lite fall ved økende ankerstrøm på grunn av spenningsfallet over ankerresistansen. For en seriemotor vil turtallet falle raskt ved økende ankerstrøm. Ved tomgang (liten ankerstrøm) vil seriemotoren ruse ut.

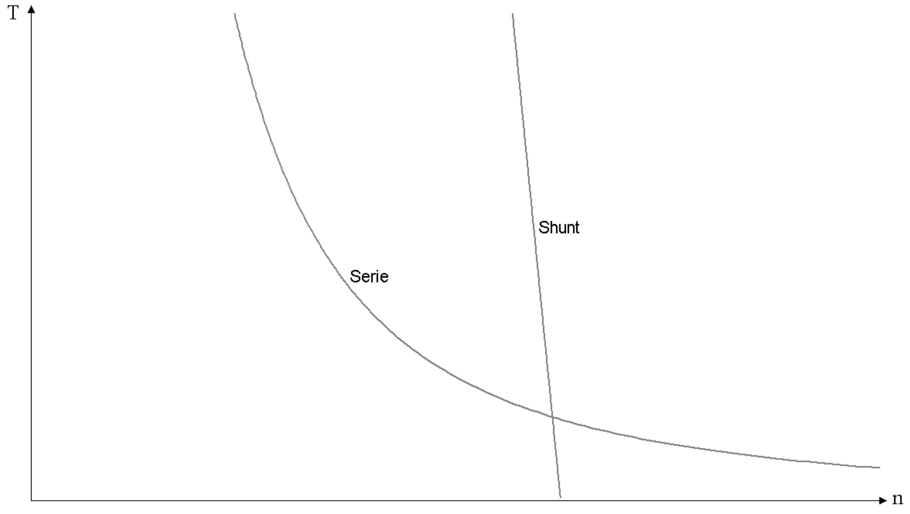
Ved oppstart vil ankerstrømmen være høy. Sammenligner en formel (12.7) og (12.8), ser en at seriemotoren har høyest startmoment. Til gjengjeld har shuntmotoren best turtallsegenskaper, slik det fremgår av formel (12.10). En kompound-motor forener det beste fra både shunt- og seriemotoren, men er en mer kostbar maskin, siden den er utstyrt med to feltviklinger.

Figur 12.9 viser drivmoment (venstre) og turtall (høyre) som funksjon av ankerstrøm for shunt- og seriemotoren.



Figur 12.9: Karakteristikker for likestrømsmotorer

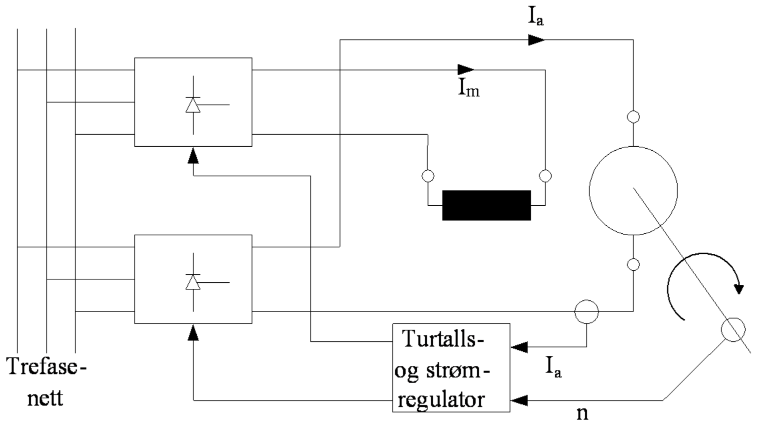
For en motor med separat magnetisering kan moment og turtall styres uavhengig av hverandre. Formel (12.4) tilsier at momentet styres ved å regulere ankerstrømmen, mens formel (12.9) viser at turtallet styres ved å regulere feltstrømmen. Til tross for komplisert oppbygning, har dette vært kommutatormaskinens store fordel, at det er mulig å styre moment og turtall uavhengig av hverandre.
Ved hjelp av dagens moderne kraftelektronikk og avanserte styresystemer kan man oppnå det samme for synkronmaskiner med permanentmagneter (børsteløs likestrømsmotor). Faktisk kan man også styre en asynkronmaskin slik at momentog turtall reguleres uavhengig av hverandre, men det kreves da et avansert styresystem med både posisjons-, strøm- og spenningssensorer. Figur 12.10 viser tilsvarende moment-turtallskarakteristikker for likestrømsmotorer. En ser at shuntmotoren varierer lite i turtall uansett belastning, mens seriemotoren faller kraftig i turtall ved økende last.



Figur 12.10: Moment-turtallskarakteristikker for likestrømsmotorer

Figur 12.11 viser et likerettersystem for en likestrøms motordrift. Siden både anker- og feltkretsen i høy grad er induktive, er det nærliggende å bruke strømmatede likerettere, og for motordrifter av likestrømsmaskiner har fullstyrte eller halvstyrte tyristorbroer vært det vanligste. Den øvre likeretterbrua styrer feltstrømmen, og den nedre styrer ankerstrømmen og motorens klemmespenning. Regulatoren måler strøm og turtall (eller vinkelhastighet) og sender styresignaler til likeretterbroene.

Eksempel 1 *En likestrøms motordrift tilkoblet et* $400/230\,\mathrm{V}$ *trefasenett benytter to halvstyrte brolikerettere. Disse forsyner henholdsvis anker- og feltkretsen på en separatmagnetisert kommutatormotor.*



Figur 12.11: Likestrøms motordrift

Det antas at induktansene i begge motorkretsene er så høy at likestrømmen er glatt. Feltstrømmen $I_m = 2,0\,\mathrm{A}$ *ved en spenning på* $50\,\mathrm{V}$ *(merkestrøm). Ankerkretsen har en merkespenning på* $220\,\mathrm{V}$*. Tilført ankereffekt ved merkedrift er* $4,5\,\mathrm{kW}$*. Total ankerresistans inklusive børster er* $10\,\Omega$*. Transformatoren har en lekkreaktans sett fra sekundærsiden på* $0,5\,\Omega$*. Regn ut styrevinklene for de to omformerne ved merkedrift.*

Løsning:
Motoren har følgende merkestrøm:

$$I_{aN} = \frac{P_{el}}{U_{aN}} = \frac{4500}{220} = 20,5\,\mathrm{A}$$

Kommuteringsspenningsfallet for ankerkretsen er

$$U_{dx,a} = \frac{3X_t I_{aN}}{\pi} = \frac{3 \cdot 0,5 \cdot 20,5}{\pi} = 9,8\,\mathrm{V}$$

Kommuteringsspenningsfallet for feltkretsen er

$$U_{dx,m} = \frac{3X_t I_m}{\pi} = \frac{3 \cdot 0,5 \cdot 2,0}{\pi} = 0,95\,\mathrm{V}$$

Tomgangslikespenningen er

$$U_{di0} = \frac{3\sqrt{3}\sqrt{2}}{\pi} U_v = \frac{3\sqrt{2}}{\pi} U_{linje} = \frac{3\sqrt{2}}{\pi} \cdot 400 = 540\,\mathrm{V}$$

Formel (6.29) definerer en styrt likespenning:

$$U_d = U_{di0} \frac{1 + \cos\alpha}{2} - U_{dx}$$

Denne løses med hensyn på α:

$$\alpha = \arccos\left(2\frac{U_d + U_{dx}}{U_{di0}} - 1\right)$$

Ankerkretsen må ha følgende styrevinkel:

$$\alpha_a = \arccos\left(2\frac{U_{aN} + U_{dxa}}{U_{di0}} - 1\right) = \arccos\left(2\frac{220 + 9,8}{540} - 1\right) = 98,6\,^\circ$$

Styrevinkelen for feltkretsen blir

$$\alpha_m = \arccos\left(2\frac{U_{fN} + U_{dx,m}}{U_{di0}} - 1\right) = \arccos\left(2\frac{50 + 0,95}{540} - 1\right) = 144\,^\circ$$

12.5 Kommutatormaskiner for vekselstrøm

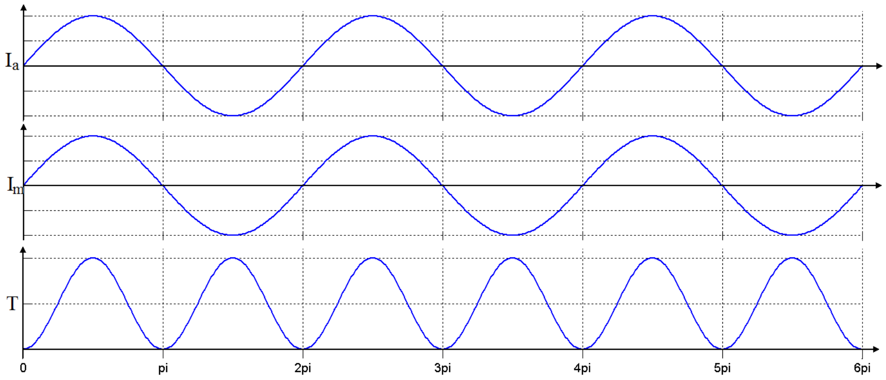
Dersom man snur polariteten til klemmespenningen på en shunt- eller seriemotor, vil både feltstrøm og ankerstrøm endre retning. Dermed vil motorens dreieretning bli som før. Dette innebærer at en shunt- eller seriemotor i teorien kan drives av en vekselspenning.
Da vil både ankerstrøm og fluks ha et sinusformet forløp:

$$\begin{gathered} I_a = \widehat{I}_a \sin(\omega t) \\ \phi = \phi_{\max} \sin(\omega t) \end{gathered} \tag{12.12}$$

Setter man formel (12.12) inn i (12.4), finner man at drivmomentet varierer på følgende måte:

$$T = k_T \phi I_a = T_{\max} \sin^2(\omega t) \tag{12.13}$$

Det fremgår av figur 12.12 at middelmomentet er halvparten av det maksimale momentet. Momentet pulserer, men treghetsmomentet i rotor gjør at motoren likevel får en jevn gange.



Figur 12.12: Vekselstrøms kommutatormotor med pulserende drivmoment

Siden både ankerstrømmen og feltstrømmen er vekselstrømmer, må også feltviklingen utstyres med laminert kjerne for å redusere virvelstrømstapene.
Når kommutatormaskinen brukes som vekselstrømsmaskin, vil det induseres en vekselspenning over ankeret i tillegg til den rotasjonsinduserte spenningen E. Årsaken er at ankerfluksen er sinusformet, og denne transformatorisk induserte spenningen er da gitt ved transformatorligningen:

$$E_{AC} = 4,44 \cdot f \cdot N \cdot \phi_{\max} \tag{12.14}$$

Denne spenningen forårsaker lysbuedannelse over børstene fordi lameller ved siden av hverandre har forskjellig spenning. En måte å redusere problemet på, er å bruke så få vindinger som mulig i ankerviklingen. Tidligere var det vanlig å bruke kommutatormaskiner ved jernbanedrift, og derfor er nettfrekvensen i jernbanenettet bare en tredjedel av vanlig nettfrekvens, altså $16,7$ Hz. Lavere frekvens bidrar nemlig også til å redusere den induserte spenningen som genereres av vekselstrømmen.
Vekselstrøms kommutatormaskiner brukes mest i håndverktøy, kjøkkenmaskiner og lignende. Det blir imidlertid stadig mer vanlig å bruke kraftelektronikk i kombinasjon med små trefasemotorer, og da kan en benytte enklere og mer robuste motortyper med langt mindre slitasje.

12.6 Øvingsoppgaver

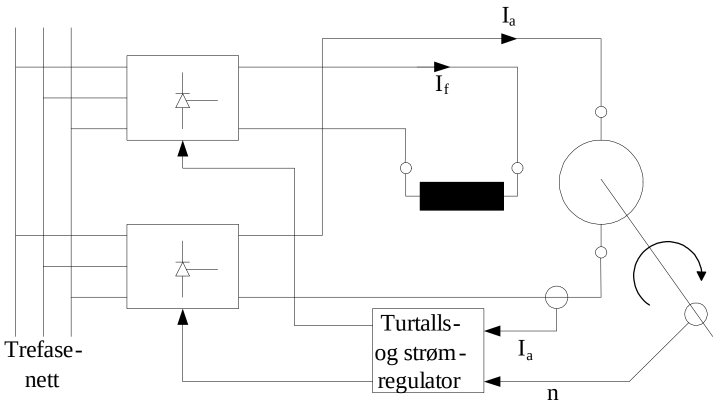
1. En kommutatormaskin med fremmedmagnetisering har en luftgapsfluks på $1,5\,\mathrm{mWb}$ og en maskinkonstant $k_E = 65$. Regn ut indusert spenning i maskinen ved et turtall på 900 o/min.

2. Maskinen i oppgave 1 har en total ankerresistans på $6,0\,\Omega$. Hvor stor blir ankerstrømmen dersom maskinen tilføres en spenning på $100\,\mathrm{V}$ når øvrige betingelser er som nevnt i oppgave 1? Går maskinen som motor eller generator?

3. En shuntmotor står tilkoblet et $220\,\mathrm{V}$ likestrømsnett og har en ankerstrøm på $10\,\mathrm{A}$ ved et turtall på 1500 o/min. Maskinen har en total ankerresistans på $3,0\,\Omega$. Hva blir turtallet dersom lastmomentet dobles?

4. Figur 12.13 viser en likestrøms motordrift hvor den øverste strømretteren styrer feltstrømmen og den nederste styrer ankerstrømmen. Forklar med utgangspunkt i (12.15) hvordan man kan styre momentet med ankerstrømmen og turtallet med feltstrømmen.

5. Hvorfor er det en fordel at ankerviklingen i en vekselstrøms kommutatormaskin har få tørn og lav frekvens?



Figur 12.13: Likestrøms motordrift

$$\begin{aligned} T &= k \cdot I_m \cdot I_a \\ n &= \tfrac{U - I_a R_a}{k' \cdot I_m} \end{aligned} \tag{12.15}$$

13 Fasit øvingsoppgaver

Kapittel 1

Oppgave 1

$\phi = 862\,\mu\mathrm{Wb}$
$B = 0,345\,\mathrm{T}$
$H_{\text{kjerne}} = 322\,\mathrm{A/\,m}$
$H_{\text{luftgap}} = 275 \cdot 10^3\,\mathrm{A/\,m}$

Oppgave 2

$e = 150\,\mathrm{V}$

Oppgave 3

$e = 2,0\,\mathrm{V}$

Kapittel 2

Oppgave 6

$\Delta P = 2,27\,\mathrm{W}$

Kapittel 3

Oppgave 3

$T = 20\,\mathrm{min}$

Oppgave 4

$\vartheta_{mask} = 46,7\,^\circ\mathrm{C}$

Oppgave 5

$\vartheta_{slutt} = 55,3\,^\circ\mathrm{C}$

Oppgave 6

$P = 31,1\,\mathrm{kW}$

Oppgave 7

15 år

Kapittel 4

Oppgave 2

$U_l = 206\,\mathrm{V}$

Kapittel 5

Oppgave 1

$N_2 = 1000$
$I_1 = 0,5\,\mathrm{A}$

Oppgave 2

$B_{\text{max}} = 1,5\,\mathrm{T}$

Oppgave 4
$e_r = 1,0\%$
$e_x = 4,57\%$
$e_z = 4,68\%$
$U_2 = 21,4\,\mathrm{kV}$

Oppgave 5
$P_{DC} = 33,4\,\mathrm{kW}$
$P_{till} = 66,\ 6\,\mathrm{kW}$
$\eta_{70\%} = 98,3\%$
$\eta_{100\%} = 98,2\%$

Oppgave 6
YNd11

Oppgave 8
$I_{1N} = 7,22\,\mathrm{A}$
$I_{2N} = 12,6\,\mathrm{A}$
$S_e = 2,13\,\mathrm{kV\,A}$

Oppgave 10
$A = 9,72\,\mathrm{cm}^2$
$A = 583\,\mathrm{cm}^2$

Kapittel 6

Oppgave 2
$230/9,5\,\mathrm{V}$
$S = 6,0\,\mathrm{V\,A}$
$C = 42000\,\mu\mathrm{F}$

Oppgave 3
$\alpha = 59,1\,°$

Oppgave 4
$d_{\max} = 0,677$
$d_{\min} = 0,323$
$L = 200\,\mathrm{mH}$

Oppgave 7
$d = 0,535$
$I_d = 5,0\,\mathrm{A}$

Oppgave 8
$14,7\,\mathrm{A}$

Kapittel 8

Oppgave 1

$E_{R+} = 228\,\text{V}\angle 0,1\,^\circ$
$E_{S+} = 228\,\text{V}\angle -119,9\,^\circ$
$E_{T+} = 228\,\text{V}\angle -239,9\,^\circ$
$E_{R-} = 40,1\,\text{V}\angle -19,8\,^\circ$
$E_{S-} = 40,1\,\text{V}\angle 100,2\,^\circ$
$E_{T-} = 40,1\,\text{V}\angle 220,2\,^\circ$

Oppgave 2

$I_R = 17,7\,\text{A}\angle 27,2\,^\circ$
$I_S = 13,3\,\text{A}\angle -97,4\,^\circ$
$I_T = 15,0\,\text{A}\angle -199,8\,^\circ$

Kapittel 9

Oppgave 1

$\frac{d\omega}{dt} = 7,27\,\text{rad/s}$

Oppgave 2

$n = 1000$ o/min
$T_{el} = T'_{last} = 20\,\text{N}\,\text{m}$
$\omega = 105\,\text{rad/s}$

Oppgave 4

$19 : 1$
$T'_{last} = 25\,\text{N}\,\text{m}$
$J_{tot} = 0,64\,\text{kg}\,\text{m}^2$

Oppgave 5

$P_{el} = 3,68\,\text{kW}$
$T_{last} = 2,45\,\text{kN}\,\text{m}$
$\omega = 1,5\,\text{rad/s}$
$n = 14,3$ o/min

Kapittel 10

Oppgave 1

$n_s = 3000$ o/min
$n_s = 1200$ o/min

Oppgave 2

$s = 5,3\%$

Oppgave 3

$f_2 = 2,67\,\text{Hz}$

Oppgave 6

$\Delta P_2 = 128\,\text{W}$

Oppgave 7
$T_{\max} = 199\,\mathrm{N\,m}$
$T_{start} = 76,5\,\mathrm{N\,m}$

Oppgave 8
$T_{\max} = 152\,\mathrm{N\,m}$
$T_{start} = 58,6\,\mathrm{N\,m}$

Oppgave 9
$\eta = 0,855$

Oppgave 11
$R_{2,ytre} = 3,0\,\Omega$

Oppgave 12
$f_1 = 46,3\,\mathrm{Hz}$
$U_1 = 370\,\mathrm{V}$

Kapittel 11

Oppgave 6
$P = 12,3\,\mathrm{MW}$
$Q = 1.75\,\mathrm{MV\,Ar}$

Oppgave 7
$Q = 6.24\,\mathrm{MV\,Ar}$

Oppgave 11
$T_{\max} = 409\,\mathrm{kN\,m} > T_{turbin}$. Maskinen er stasjonært stabil.

Kapittel 12

Oppgave 1
$E = 88\,\mathrm{V}$

Oppgave 2
$I_a = 2,0\,\mathrm{A}$

Oppgave 3
$n = 1260$ o/min

Register

F Wiring Schematics

HPEVS
HI PERFORMANCE ELECTRIC VEHICLE SYSTEMS
1551 S. Vineyard Avenue
Ontario, CA 91761
(909) 923-1973

WIRING SCHEMATICS

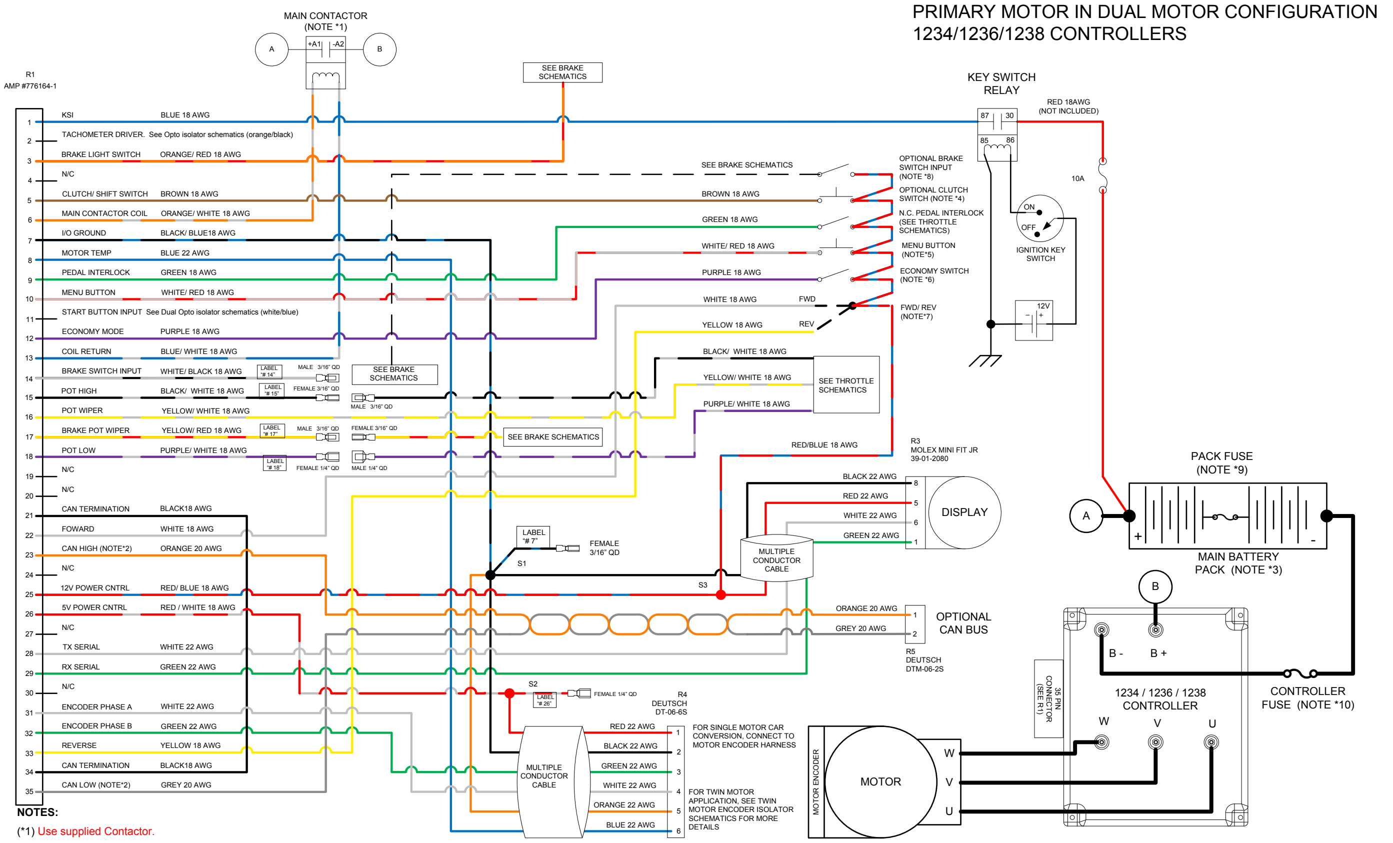
ON-ROAD VEHICLE CONVERSION SINGLE AND DUAL MOTOR APPLICATION

FOR SOFTWARE VERSIONS 5.13 AND HIGHER

FOR CURTIS CONTROLLERS 1234/1236/1238

REVISION: D
Date: 5/28/14

ELECTRICAL SCHEMATICS FOR SINGLE MOTOR OR PRIMARY MOTOR IN DUAL MOTOR CONFIGURATION 1234/1236/1238 CONTROLLERS



NOTES:

(*1) Use supplied Contactor.

(*2) The Controller CAN Communication needs to be isolated from other CAN based components. A CAN isolator may be needed.
Possible source of CAN isolator is CANOP from B&B Electronics (www.bb-elec.com)

(*3) A Battery Management System (BMS) is strongly recommended if Lithium Ion batteries are used. Possible source of BMS is Ewert Energy System's ORION BMS (www.orionbms.com)

(*4) Install the Clutch/ Shift Switch so that is ON when the clutch pedals is pressed. When clutch pedal is pressed the Regen setting is changed to Shift Neutral Braking Parameter to prevent the motor from stalling during gear shifting. In a Clutch-less system, this allows you to set the coast down rate of the motor so that the gears align properly See Instructions on SHIFT-NEUTRAL BRAKING PARAMETERS.

(*5) Gives access to Drive System information. Required to access Programming and Diagnostic modes. See Programming Instructions.

(*6) Allows the use of ECONO Mode Parameters. See Programming Instructions.

(*7) Forward is CLOCKWISE motor rotation from Encoder end view. Depending on Transmission configuration, use either wire to obtain desired rotation. Use FWD & REV Switch in direct drive applications.

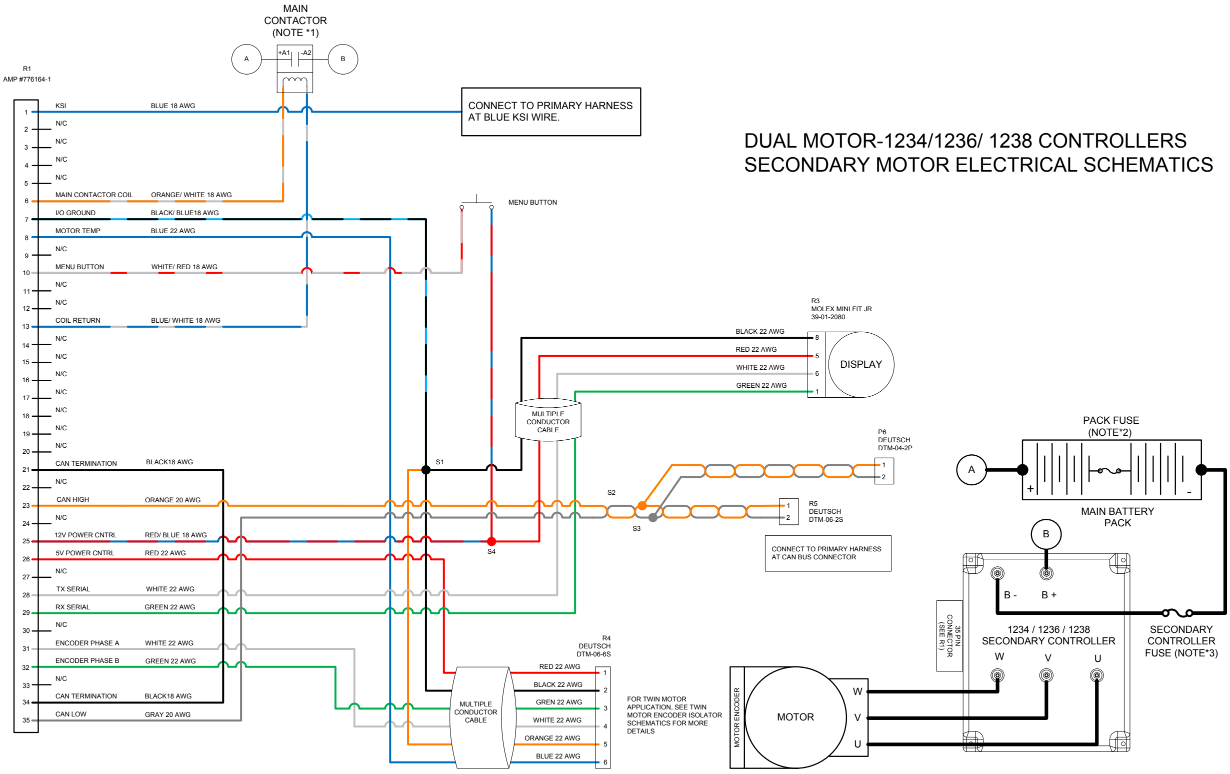
(*8) See Brake Schematics.

(*9) Use Pack Fuse rated at 500A for Single controller applications. For Dual controller use 800A Pack Fuse.

(*10) Only for Dual motor application. Use Controller Fuse rated at 500A for each controller.

CAD TYPE VISIO	APPLICABLE SOFTWARE	VERSION 5.13	
UNIT NONE	DRAWING	1010-AUTO-CONVERSION	
DRW SIZE A	TITLE	ON-ROAD VEHICLE CONVERSION / PRIMARY DUAL MOTOR SCHEMATICS	
DATE 2/12/13			
SUPPLIER PART	HW-AUTOCONVERSION-HPG		
SCALE NONE	SHEET 1 OF 1	REVISION D	**HPEVS**

DUAL MOTOR-1234/1236/ 1238 CONTROLLERS
SECONDARY MOTOR ELECTRICAL SCHEMATICS



NOTES:

(*1) USE SUPPLIED CONTACTOR

(*2) Use Pack Fuse rated at 500A for Single controller applications. For Dual controller use 800A Pack fuse.

(*3) Only for Dual motor application. Use Controller Fuse rated at 500A for each controller.

CAD TYPE VISIO	APPLICABLE SOFTWARE	VERSION 5.13	
UNIT NONE	DRAWING	1010-AUTO-CONVERSION-TWIN MOTOR	
DRW SIZE A	TITLE	SECONDARY DUAL MOTOR SCHEMATICS	
DATE 4/2/13			
SCALE 1:1	SHEET 1 OF 1	REVISION B	**HPEVS**

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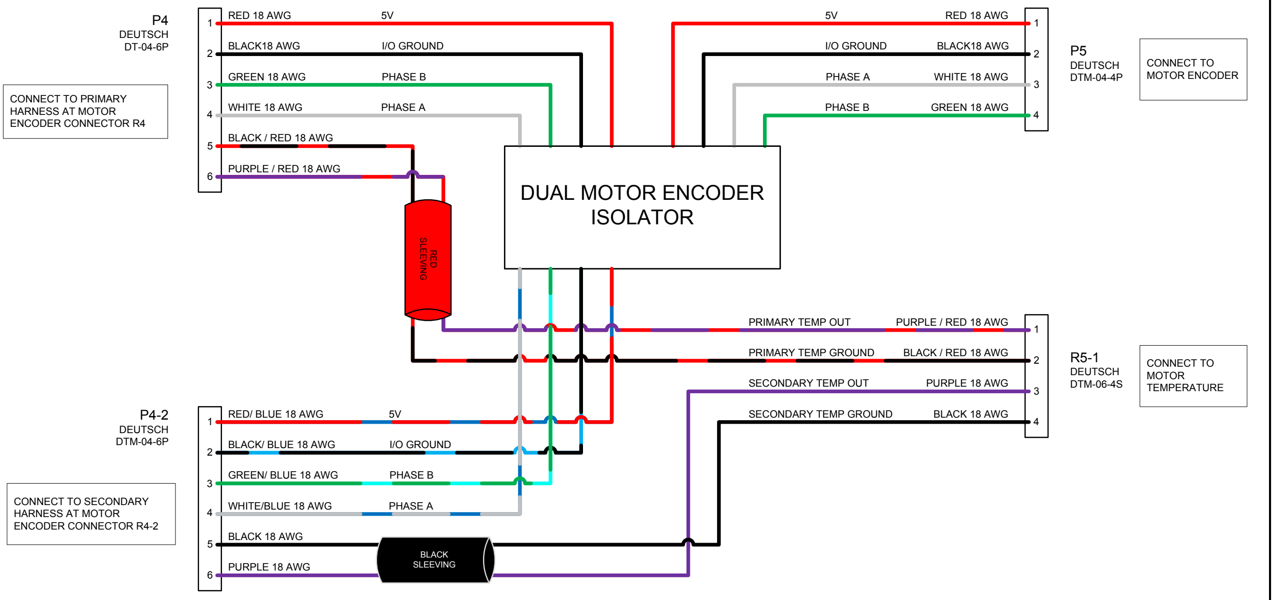

CAD TYPE VISIO	CAD LOC.	APPLICABLE SOFTWARE	DRW SIZE B
OPER. NO.	UNIT	DRAWING 1010-TWIN-ENCODER-ISOLATOR	
DESIGN	DETAIL	TITLE DUAL MOTOR ENCODER ISOLATOR SCHEMATICS	
CHECKED	SAFETY		
SCALE NONE	DATE 4/2/2013	REVISION A SHEET 1 OF 1	HPEVS

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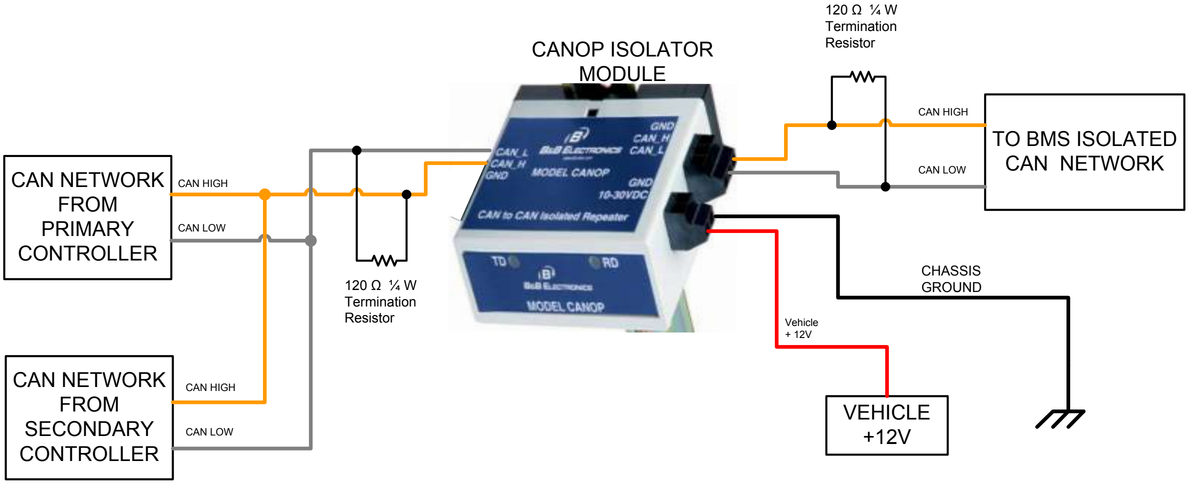
REVISIONS

REV	DESCRIPTION	APPROVED
A	INITIAL RELEASE	3/11/2013
B	Revision for clarification	10/30/2013



CAD TYPE VISIO	CAD LOC.	CAD FILE	DRW SIZE A
OPER. NO.	UNIT	DRAWING 1010-CAN-OP-ISOLATOR	
DESIGN	DETAIL	TITLE CAN ISOLATOR DUAL 1238 CONTROLLER	
CHECKED	SAFETY		
SCALE NONE	DATE 4/17/13	REVISION B SHEET 1 OF 1	**HPEVS**

THROTTLE CONFIGURATION

Depending on the type of throttle used for the application, the different types of throttle configurations are listed within the table below. Electrical schematics are also included within the following pages.

THROTTLE CONFIGURATION	**TYPE**
ELECTRONIC without SWITCH	TYPE 1
2 WIRE with SWITCH 0-5k Ω	TYPE 2
3 WIRE with SWITCH 0-5k Ω	TYPE 3
CURTIS PB8 THROTTLE ASSEMBLY	TYPE 3

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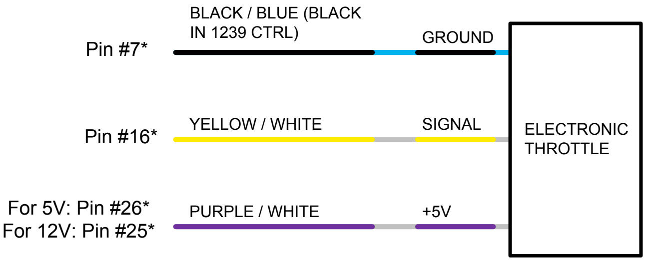
REVISIONS

REV	DESCRIPTION	APPROVED
A	INITIAL RELEASE	1/22/2013

TYPE 1 ELECTRONIC THROTTLE**



* Typical connection, verify correct voltage and connection in throttle documents or instructions.

Not all Electronic Throttles supported

** When an electronic pedal is used, the GREEN wire from pedal interlock does not need to be connected

CAD TYPE VISIO	APPLICABLE SOFTWARE		
UNIT NONE	DRAWING 1010-THROTTLE-001		
DRW SIZE A	TITLE ELECTRONIC THROTTLE		
DATE 1/22/13			
SUPPLIER PART			
SCALE NONE	SHEET 4 OF 4	REVISION B	**HPEVS**

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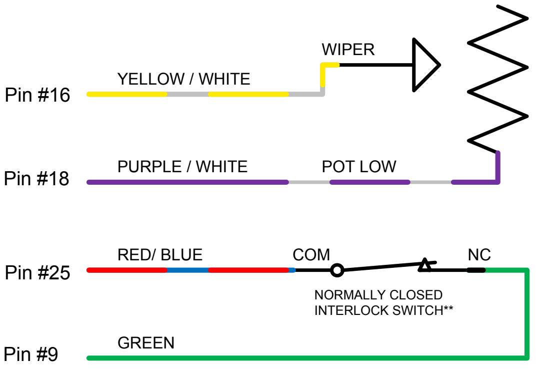
REVISIONS		
REV	DESCRIPTION	APPROVED
A	INITIAL RELEASE	1/22/2013

2 WIRE TYPE 2 THROTTLE



** When the accelerator pedal IS PRESSED the interlock switch is released to its NORMAL position (switch not activated) thus completing the circuit since its green wire is connected to the normally closed (NC) connection.

CAD TYPE VISIO	CAD LOC.	CAD FILE	DRW SIZE A
OPER. NO.	UNIT	DRAWING 1010-THROTTLE-001	
DESIGN	DETAIL	TITLE 2 WIRE TYPE 2 THROTTLE	
CHECKED	SAFETY		
SCALE NONE	DATE 1/22/13	REVISION A SHEET 1 OF 3	HPEVS

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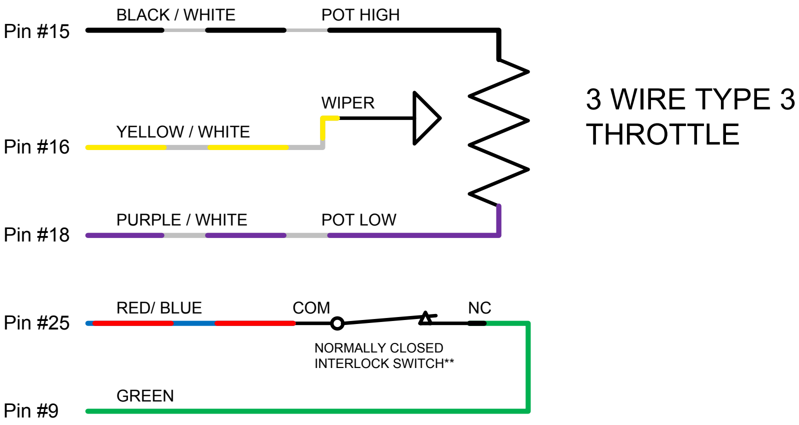
REVISIONS		
REV	DESCRIPTION	APPROVED
A	INITIAL RELEASE	1/22/2013



** When the accelerator pedal <u>IS PRESSED</u> the interlock switch is released to its <u>NORMAL</u> position (switch not activated) thus completing the circuit since its green wire is connected to the normally closed (NC) connection.

CAD TYPE VISIO	CAD LOC.	CAD FILE	DRW SIZE A
OPER. NO.	UNIT	DRAWING 1010-THROTTLE-001	
DESIGN	DETAIL	TITLE 3 WIRE TYPE 3 THROTTLE	
CHECKED	SAFETY		
SCALE NONE	DATE 1/22/13	REVISION A SHEET 2 OF 3	**HPEVS**

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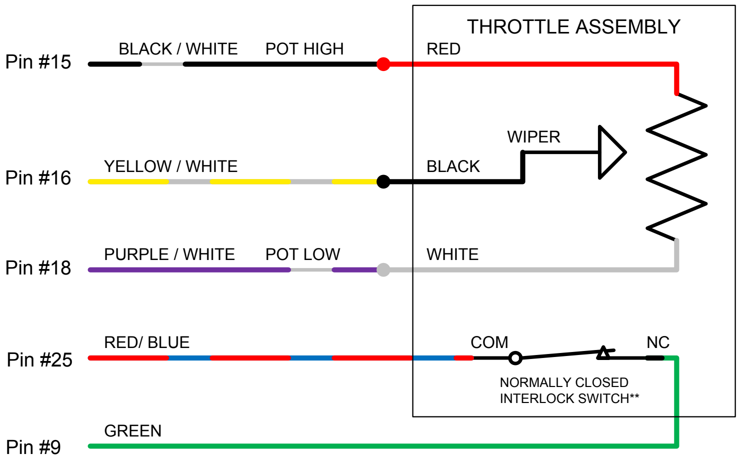
REVISIONS		
REV	DESCRIPTION	APPROVED
A	INITIAL RELEASE	11/27/2013



CURTIS PB8
THROTTLE
ASSEMBLY

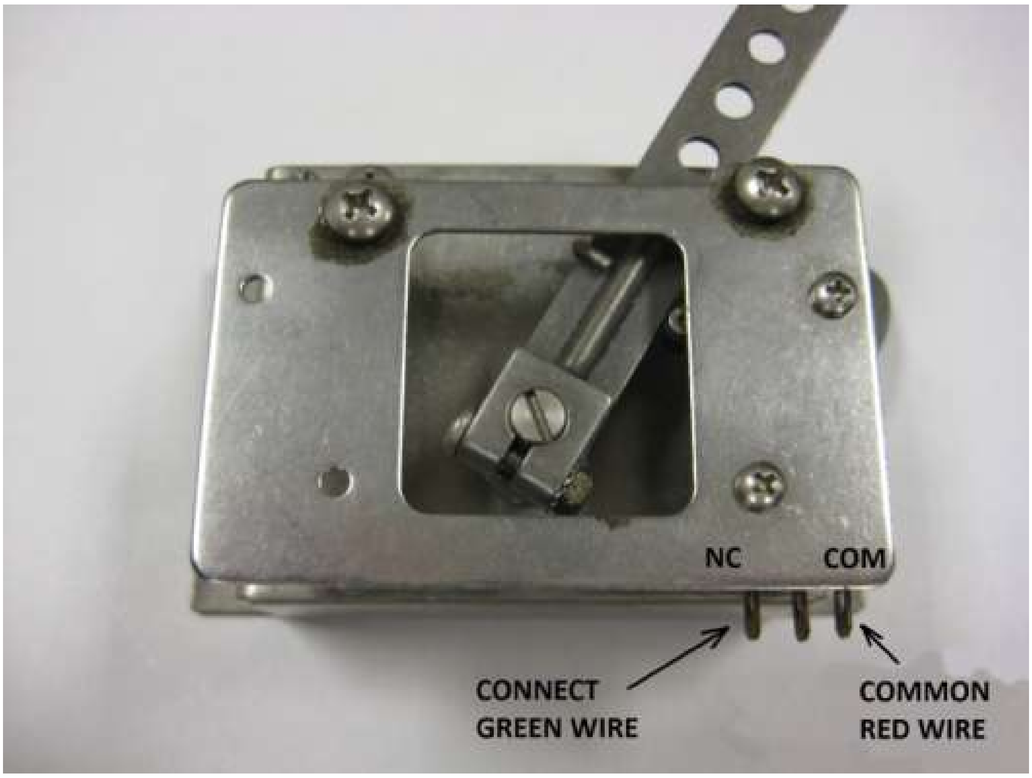
** When the accelerator pedal IS PRESSED the interlock switch is released to its NORMAL position (switch not activated) thus completing the circuit since its green wire is connected to the normally closed (NC) connection.

CAD TYPE VISIO	APPLICABLE SOFTWARE		
UNIT NONE	DRAWING 1010-THROTTLE-001		
DRW SIZE A	TITLE CURTIS PB8 THROTTLE ASSEMBLY		
DATE 1/22/13			
SUPPLIER PART			
SCALE NONE	SHEET 3 OF 4	REVISION A	**HPEVS**

PEDAL INTERLOCK CONNECTION

The pedal interlock connection is required for both 2 and 3 wire throttle pot assemblies. The Green wire is connected to the Normally Closed tab. The red/blue wire is connected to the common tab. See picture below.

NOTE: when the accelerator pedal IS PRESSED the interlock switch is released to its NORMAL position (switch not activated) thus completing the circuit since its green wire is connected to the normally closed (NC) connection.



BRAKE INPUT CONFIGURATION

Depending on the type of brake input used for the application, the different types of brake input configurations are listed within the table below. Electrical schematics are also included in the following pages.

BRAKE INPUT CONFIGURATION	**TYPE**
NO BRAKE POT INSTALLED	TYPE 0
PRESSURE TRANSDUCER/ ELECTRONIC 0-5V INPUT	TYPE 1
2 WIRE 0-5k Ω POT	TYPE 2
SWITCH	TYPE 3

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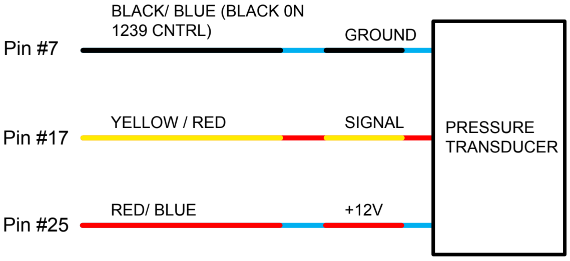
REV	DESCRIPTION	APPROVED
A	INITIAL RELEASE	2/19/2013



TYPE 1
PRESSURE
TRANSDUCER

** Typical Pressure Transducer Ratings
8-30 Volt Input
1-5 Volt Output
2500 PSI

CAD TYPE VISIO	CAD LOC.	CAD FILE	DRW SIZE A
OPER. NO.	UNIT	DRAWING 1010-BRAKE	
DESIGN	DETAIL	TITLE PRESSURE TRANSDUCER	
CHECKED	SAFETY		
SCALE NONE	DATE 2/19/13	REVISION A SHEET 2 OF 2	HPEVS

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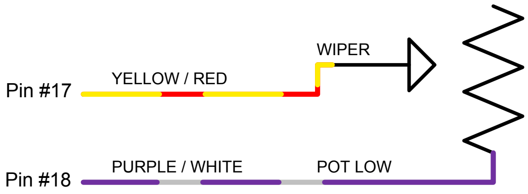
REVISIONS		
REV	DESCRIPTION	APPROVED
A	INITIAL RELEASE	2/19/2013



TYPE 2
2 WIRE BRAKE POT

CAD TYPE VISIO	CAD LOC.	CAD FILE	DRW SIZE A
OPER. NO.	UNIT	DRAWING 1010-BRAKE	
DESIGN	DETAIL	TITLE 2 WIRE BRAKE POT	
CHECKED	SAFETY		
SCALE NONE	DATE 2/19/13	REVISION A SHEET 1 OF 2	**HPEVS**

OPTIONAL ACTIVE BRAKE LIGHT CONFIGURATIONS

These optional active brake light configurations are used to activate the brake lights during regenerative braking or when the vehicle brakes are being applied. Based on the brake type configuration that is being used in the application use one of the following wiring configurations.

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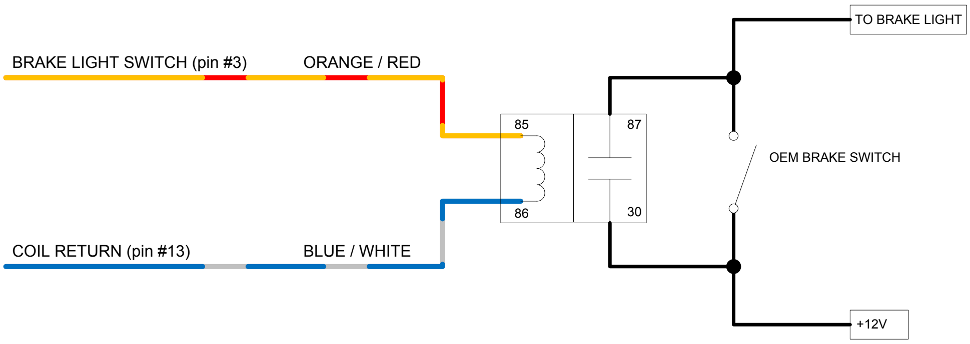
ACTIVE BRAKE LIGHT CONFIGURATION
OPTION 1
FOR BRAKE TYPE 0, 1 OR 2 CONFIGURATIONS

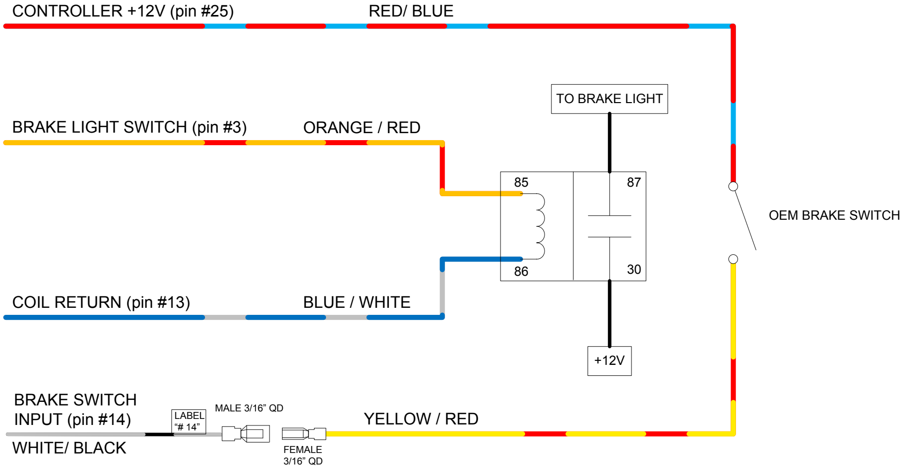


** This option turns the brake lights ON during REGEN. Brake TYPE 0 does not allow for BOOSTED BRAKE while pressing the brake pedal. Brake TYPE 1 & 2 uses a variable input for BOOSTED REGEN.

CAD TYPE VISIO	CAD LOC.	CAD FILE	DRW SIZE A
OPER. NO.	UNIT	DRAWING 1010-BRAKE	
DESIGN	DETAIL	TITLE OPTION 1 BRAKE LIGHT SWITCH	
CHECKED	SAFETY		
SCALE NONE	DATE 12/5/13	REVISION A SHEET 3 OF 4	**HPEVS**

REVISIONS		
REV	DESCRIPTION	APPROVED
A	INITIAL RELEASE	2/19/2013

ACTIVE BRAKE LIGHT CONFIGURATION
OPTION 2
FOR BRAKE TYPE 3
1234, 1236, &1238 CONTROLLER



** This option will turn ON the brake lights when either of two conditions are satisfied:

1. The users foot is OFF of the accelerator pedal and REGEN is active.
2. Brake pressure is applied and the OEM brake switch is active.

CAD TYPE VISIO	CAD LOC.	CAD FILE	DRW SIZE A
OPER. NO.	UNIT	DRAWING 1010-BRAKE	
DESIGN	DETAIL	TITLE OPTION 2 BRAKE LIGHT SWITCH 1234,1236, &1238 CONTROLLER	
CHECKED	SAFETY		
SCALE NONE	DATE 12/5/13	REVISION A SHEET 3 OF 4	**HPEVS**

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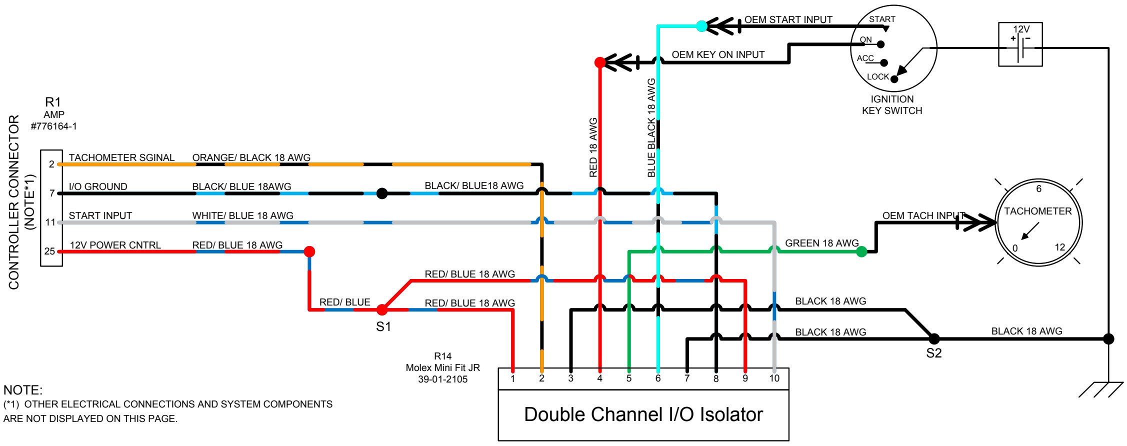

NOTE:
(*1) OTHER ELECTRICAL CONNECTIONS AND SYSTEM COMPONENTS ARE NOT DISPLAYED ON THIS PAGE.

I/O ISOLATOR PIN FUNCTION

1 – CHANNEL 1 CONTROLLER 12V
2 – CHANNEL 1 TACHOMETER SIGNAL
3 – CHANNEL 1 GROUND
4 – CHANNEL 1 VEHICLE 12V
5 – CHANNEL 1 OUTPUT TO TACHOMETER
6 – CHANNEL 2 IGNITION KEY INPUT
7 – CHANNEL 2 GROUND
8 – CHANNEL 2 CONTROLLER I/O GROUND
9 – CHANNEL 2 CONTROLLER 12V
10 – CHANNEL 2 CONTROLLER START INPUT

CAD TYPE VISIO	CAD LOC.	CAD FILE	DRW SIZE B
OPER. NO.	UNIT	DRAWING 1010-2CH-ISOLATOR-001	
DESIGN	DETAIL	TITLE DUAL CHANNEL OPTO-ISOLATOR SYSTEM SCHEMATICS	
CHECKED	SAFETY		
SCALE NONE	DATE 4/19/12	REVISION B SHEET 1 OF 1	**HPEVS**

G Part list/order list

Equipment list

Shop	Part name	Part number	Part description	Price per piece	Volume	Currency	Sum
EV West	Active Vehicle Side Control Board Module AVC2 for public charge	J1772	The control module for safe charging interlock, soft start and stop, and activating the light around the charge i	$45.00	1	$	45,00
	Billet Aluminium Throttle Potentiometer		Potentiometer forelectromechanical assembly.	$199.00	1	$	199,00
	Mennekes European 32A Receptable With Cover		Charging socket vehicle side, male pins. For mount to replace fuel cap on fuel tank.	$119.00	1	$	119,00
	Universal Ball and Socket for EV Throttle Control Lever		Coupling between throttle wire and pot-meter arm.	$29.00	1	$	29,00
	Red Terminal Boot Large (up to 120mm2)		Rubber isolation hood for wire and poles.	$8.00	7	$	56,00
	Black Terminal Boot Large (up to 120mm2)		Rubber isolation hood for wire and poles.	$8.00	1	$	8,00
	Rincon Power	HVBD4AXR	Main Switch for Batteries, 400 A Continuous, 1000V Max Hermetically Sealed Disconnect Switch.	$159.00	1	$	159,00
	Gigavac GV-QA EV Contactor		Contactor for 4000 Amps max, 48 V External Economizer PWM	$179.00	1	$	179,00
	Gigavac GV200-PA EV Contactor		4000 Amps max, 12 V External Economizer PWM.	$114,88	1	$	114,88
	600 Amp 50MV Shunt		Shunt bridge for positive pole.	$47.00	1	$	47,00
	Rail Mount Ultra Safe Fuse Holder High Voltage Low Current		Rail monted fuse holder to be mounted in a sealed box	$16.88	3	$	50,64
	High Voltage Low Current EV Fuse 600V 30 Amp	ATM30	Fuse for rail mounted fuse holder.	$11.80	2	$	23,60
	High Voltage Low Current EV Fuse 600V 10 Amp	ATM10	Fuse for rail mounted fuse holder.	$11.80	1	$	11,80
	Elcon 6.6kW UHF Pre Programmed (125v) Charger	UHF33-125	On-board pre programmed charger, output voltage range 33-132 V.	$1,500.00	1	$	1500,00
	Tesla Model S Lithium Ion Battery 18650 EV Module	Tesla MS	Configuration 74p6s, 22.8 Volt, 5.3 kWh.	$1,580.00	4	$	6320,00
	DC/DC Converter 1000W Isolated 74 – 162 Volts		Converter to supply the 12 Volt harness/circuits.	$549.00	1	$	549.00
						Sum EV West=	8861,92
Otto Expert Excellence	HFNR - Forward / Neutral / Reverse Hall Effect Switch		Dashboard mounted switch for forward-neutral-reverse		1		
	P6 Limit Switch Noteworthy Designs		End switch for throttle to toggle on/off regeneration when throttle is at rest		1		
Marineshop	Dødmannsknapp	110341	Switch for shutdown if driver falls off	kr. 198,00	1	kr.	198,00
Grandado	Trykksensor	8720218266938	Brake pressure sensor to activate brake light.	kr.415,00	1	kr.	415,00
Mekonomen	T-stykke	04-Q3X-M12	T-coupling to mount pressure sensor and system ventilator together.	kr.621,00	1	kr.	621,00
	Union		Coupling between caliper and T-coupling				
Biltema	Tenningslås	25-234	Key operated switch, with LED indicator for state. 12V, 10A	kr.199,00	1	kr.	199,00
Trama in Harstad	Kramp, Simplex tannhjul Z40	SE1240	Gears for the transmission.		2		
	Kramp, 1/2" x 5/16" rullekjede rustfri	08B1RP	Chain for the transmission.		1meter		


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EDGE 136
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