UiT
THE ARCTIC
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Department of Electrical Engineering

All electric battery service vessel

Dynamic modeling of a battery fed IPMSM propulsion plant as a tool for energy estimates and functional description for an energy management system

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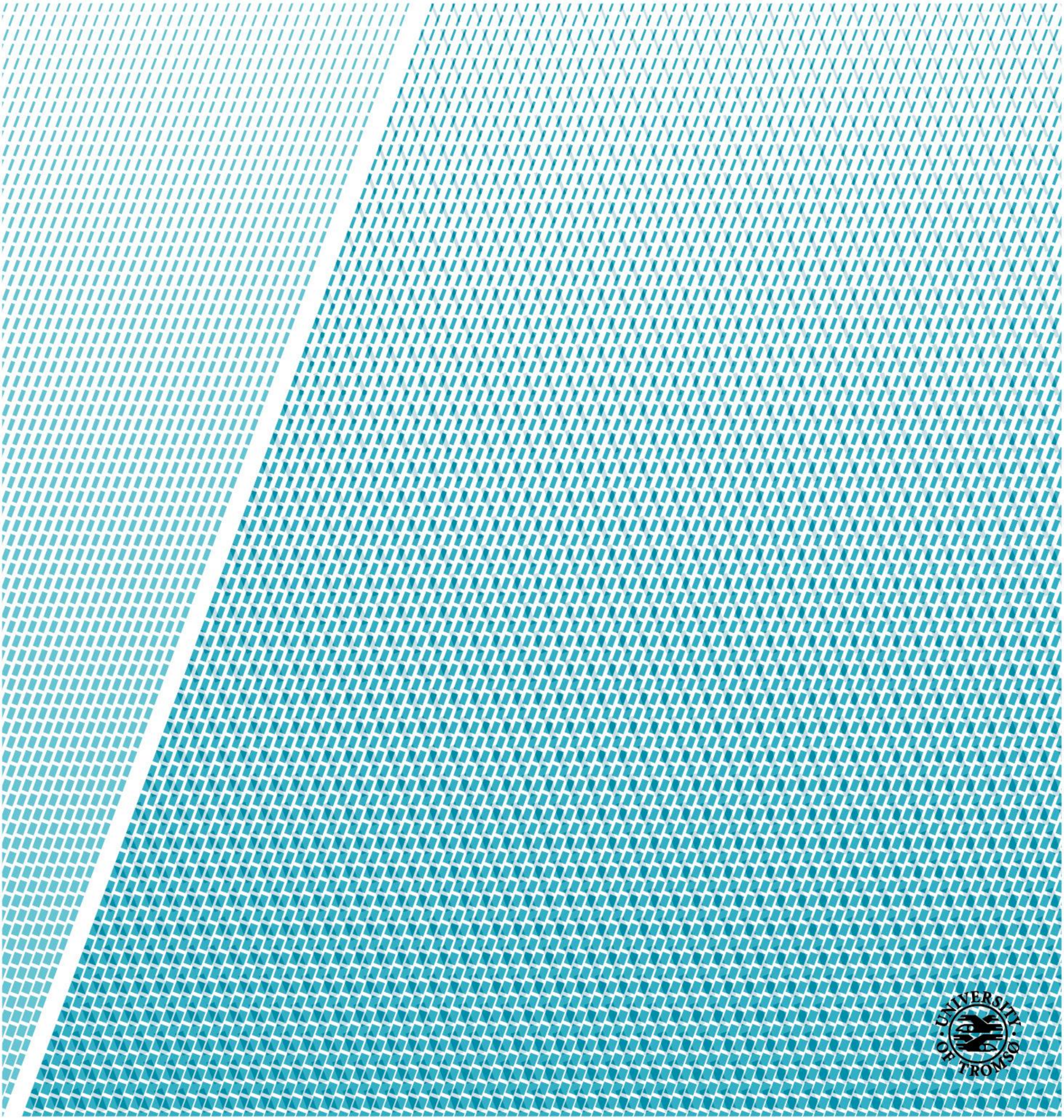
Master's thesis in Electrical Engineering June 2017



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Last, I am grateful for the friends I have made in school, and for the friendships that I've kept despite school. Finally, I shall have time to spend with you all.

Narvik, 6th of June 2017

Anders Breines

ABSTRACT

Designing an all-electric battery vessel, knowledge of the dynamic performance of the electrical propulsion plant becomes crucial to produce adequate estimates of needed battery capacity. An energy management system is to control the on-board power flow and ensure energy efficient operation of the vessel. This thesis presents a solution for dynamic simulation of an all-electric battery vessel based on an internal permanent magnet synchronous machine propulsion plant.

Insight in system dynamics forms the basis of a proposed functional description for further design of an energy management system. Through description of the different modes and transitions between them, critical aspects and functionality of the control system are enlightened.

The thesis presents a tuning guide showing how to tune the model to convergence using measured data from the vessel sea trial. When tuned, the presented model can be used for dimensioning future battery vessels.

The model is designed in MATLAB Simulink.

Key words: ***Energy management system, dynamic modeling, battery vessel, IPMSM, electric propulsion*****.**

ABBREVIATIONS

GMV	Grovfjord Mek. Verksted
EMS	Energy Management System
BMS	Battery Management System
PMSM	Permanent Magnet Synchronous Machine
IPMSM	Internal Permanent Magnet Synchronous Machine
PWM	Pulse Width Modulation
MTPA	Maximum Torque Per Ampere
NMC	Short for LiNiMnCo, alloy of Lithium, Nickel, Manganese and Cobalt
BBC	Buck Boost Converter
CRC	Charging Rectifying Converter
HPU	Hydraulic Pressure Unit
SFC	Static Frequency Converter
VSD	Variable Frequency Drive
PVSD	Propulsion Variable Frequency Drive
TVSD	Thruster Variable Frequency Drive
MCB	Miniature Circuit Breaker
HMI	Human Machine Interface, often used for touch sensitive operating screen
EMF	Electromotive Force
SOLAS	Safety Of Life At Sea, maritime convention
MARPOL	Maritime convention for the prevention of pollution from ships
STCW	The International Convention on Standards of Training, Certification and Watchkeeping for Seafarers
ISM	International Safety Management code, maritime convention
ISPS	International Ship and Port Facilities Security Code, maritime convention

NOMENCLATURE

I	Current [A]
V	Voltage [V]
P	Power [W]
t	Time [s]
τ	Torque [Nm]
m	Mass [kg]
ω	Mechanical angular velocity [rad/s]
η	Efficiency
k	Peukert constant
p	No. of magnetic poles
C_p	Battery capacity [Ah]
ω_{el}	Electrical angular velocity [rad/s]
θ_{el}	Electrical angle [rad]
C_p	Battery capacity [Ah]
J	Propeller advance coefficient
K_T	Propeller thrust coefficient
K_Q	Propeller torque coefficient
THP	Thrust horsepower
DHP	Delivered horsepower
η_0	Open water propeller efficiency
V_a	Vessel speed of advance [m/s]
$R_{(V_a)}$	Hull water resistance as a function of V_a [Nm]
J	Moment of Inertia [kg/m^2]
F_{Prop} , F_{Thrust}	Propulsive thrusting force [N]
τ_{Prop}	Propeller load torque [Nm]
τ_{el}	Electrical drive torque [Nm]
D_d	Viscous damping constant [Nms/rad]
τ	Torque [Nm]
R_a	IPMSM stator resistance
v_a, v_b, v_c	Motor terminal voltage [V]
v_d, v_q	d and q axis voltages [V]
i_d, i_q	d and q axis currents [A]
L_d, L_q	d and q axis inductances [H]
λ_d, λ_q	d and q axis flux linkages [Wb-t]
λ_f	Amplitude of the permanent magnet flux linkage [Wb-t]

TABLE OF CONTENT

1 INTRODUCTION

1.1 BACKGROUND

Grovfjord Mek. Verksted AS is a shipyard in Grovfjord constructing service vessels for the fish farming industry. They are now building their first fully electrical version of this vessel type. Electric propulsion and electrical cranes or winches, is not unusual on modern ships. The innovation specifically, will be the type of energy storage. Lithium batteries will store and supply all the energy needed for propulsion and equipment. UiT Campus Narvik are to develop and program the energy management system (EMS) for the vessel. This can be considered the equivalent for power management systems (PMS) in conventional maritime electrical system design. Assisting this development, this thesis will aim to provide a multi-purpose dynamic model of the vessels energy flow. Insight, gained developing the dynamic model, will further be used to present an EMS functional description.

1.2 RESEARCH QUESTION

1.2.1 ORIGINAL TOPIC DESCRIPTION

Energy flow analysis and simulation for battery powered vessel

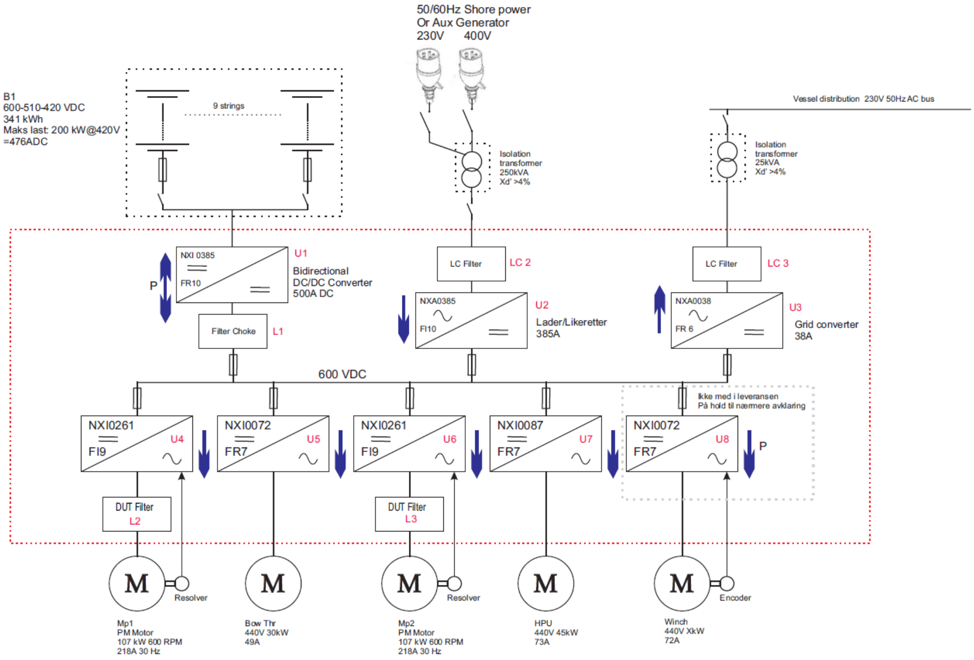


FIGURE 1 – CIRCUIT DIAGRAM FOR BATTERY POWERED VESSEL

A prototype service boat for the fish farm industry is under construction. It will be fully powered by batteries and will be charged every time the boat docks. The main on-board network is a 600 V DC grid. A bi-directional DC-DC converter boosts the battery voltage and energizes the DC-bus during operation. In harbour mode, the DC-bus is energized through an active rectifier connected to the on-shore grid. In this mode, the DC-DC-converter acts as a battery charger. All the thrusters as well as the hydraulic pump are driven by inverters. Yet another inverter is generating 230 V AC for the internal AC-grid.

The energy system of the ship should be modelled and simulated. A wide range of operational modes are to be simulated, to observe how different state variables are affected. The state of charge of the batteries and the range of the vessel should also be estimated.

The topic has some similarities with off-line microgrids, except that the system contains no energy sources.

The topic is suitable for one person in the field of electrical engineering/power systems.

Supervisor: Trond Østrem

1.2.2 REFINEMENT AND FINAL RESEARCH QUESTIONS

During the project, it became obvious that the precision of a dynamic model would be very low without accurate data for the hull and propeller dynamics. Modeling the vessel system performance during various conditions would give valuable system insight and understanding, but could not produce trustworthy result regarding energy consumption. Simulated data could not be used for dimensioning of the capacity of the batteries. If the model, on the other hand, was designed as a multi-purpose model, it could serve as a tool for dimensioning and system design. This would require a tuning procedure, to match the physical parameters in the model to the measured ones. Thus, creating a dynamic model still has its purpose. This leads to the first research question: Create a multi-purpose dynamic model of a battery vessel with IPMSM motor propulsion.

Creating this model would give valuable insight in system performance and necessary precautions in design of the energy management system. This insight could be used as basis to prepare a specified function list for the final control system. The second research question is therefore: Prepare a functional description for the necessary functionality of an energy management system in such a vessel.

2 THEORY

2.1 INTERNAL PERMANENT MAGNET SYNCHRONOUS MACHINE

Permanent magnet synchronous machines (PMSM) have become important for applications which requires highly dynamic variable speed drives. Of all electrical machines available on the market, these offer the highest torque per volume. This is achieved by exploiting their rotor saliency. Rare earth magnet materials are used as excitation in the rotor. Neodymium-Iron-Boron materials have excellent magnetic properties for rotor excitation and contributes to the compact design of these machines. Both surface mounted and internally mounted permanent magnets are used. IPMSM are machines with internally mounted permanent magnets. Mounting the magnets internally, makes the rotor field more sinusoidal distributed and makes it easier to counteract the field from the permanent magnets. By applying field oriented control, the field can be weakened as desired. This makes the machine ideal for applications which requires a wide speed range combined with high torque production. By applying a maximum torque per amp (MTPA) control strategy, an IPMSM operates at efficiencies above 0.96 in a wide speed range (Haque & Rahman, 2009).

2.2 BI-DIRECTIONAL DC/DC CONVERTER

A DC/DC converter is a switch mode power converter capable of transforming a DC voltage from one voltage level to another. Depending on whether the voltage rises or decreases from the input to the output, the converter is referred to as buck or boost. Buck converters are designed to reduce the voltage level and boost converters are designed to increase the voltage. Further classification of DC-converters considers the voltage polarity and current direction. Bi-directional converters can handle power flow in two directions, both to and from the source. Four possible quadrants of operation and combinations are shown in figure 2.

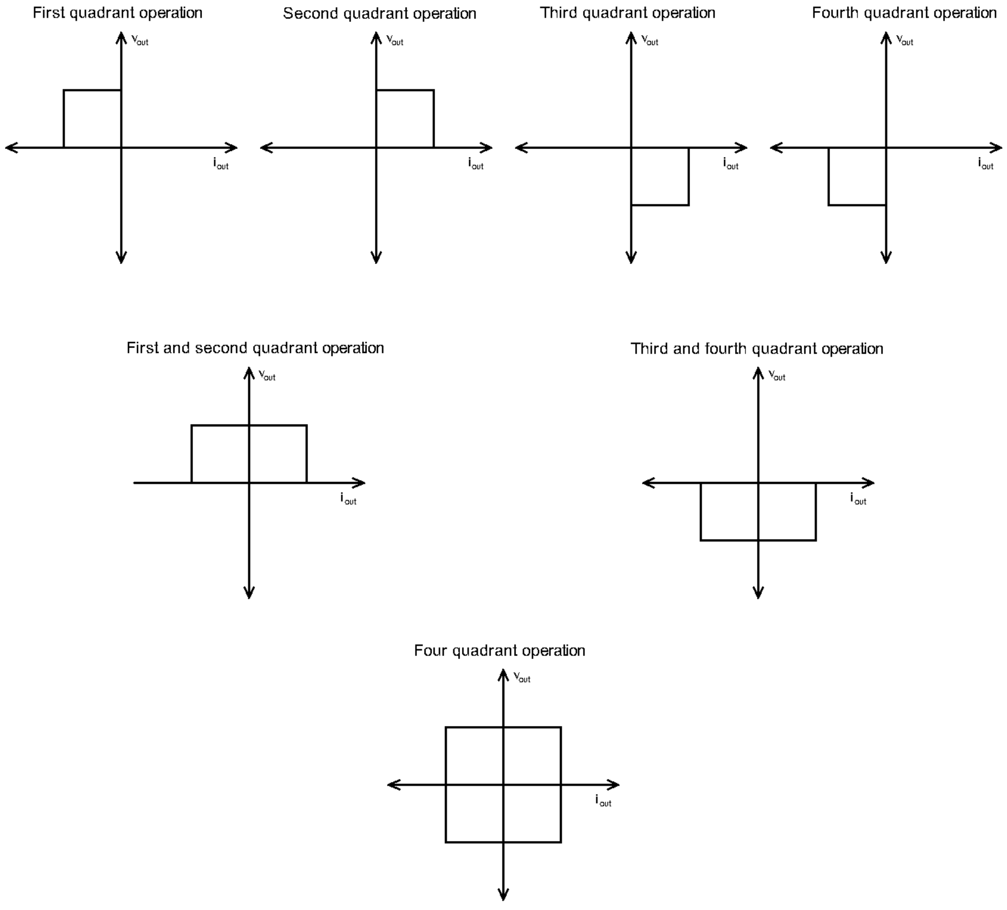


FIGURE 2 – OPERATION QUADRANTS OF DC-DC CONVERTERS

While battery terminal voltage varies with loading and state of charge, a DC/DC converter can be used to produce a stable voltage on the output for a wide range of battery terminal voltages. Rechargeable applications require two quadrants of operation. By operating in first or second quadrant, the current flow in either directions while the output voltage remains constant. This can be achieved using two converters or a bi-directional converter capable of operating in both first and second quadrant.

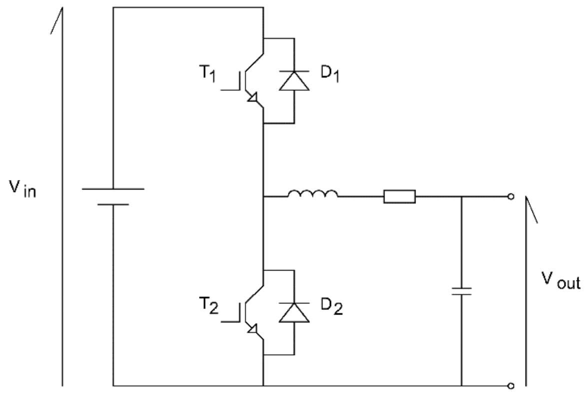


FIGURE 3 – PRINCIPAL OF BIDIRECTIONAL DC-DC CONVERTER OPERATING IN FIRST AND SECOND QUADRANT

The principal of such a bi-directional converter is shown in figure 3. By pulse width modulation (PWM) of transistor T_1 and T_2, the voltage on the output terminals can be controlled. To operate in the second quadrant, meaning a current flow towards the battery, the load need to be active. It must be able to operate as a continuous source of power (Krishnan, 2001). A DC-bus with several possible feeding points is an example of a such load.

2.3 LITHIUM ION BATTERY

2.3.1 GENERAL CONCEPT

A battery is an electrochemical energy storage. It consists of a cathode, anode and an electrolyte. For rechargeable battery cells, the electrodes' electrochemical role changes from anode to cathode and vice versa, depending on whether the battery is charging or discharging. The convention, however, is not changing. On rechargeable batteries, the positive terminal during the discharge cycle is referred to as the cathode. The term lithium battery is used to describe all batteries built from cells with a lithium alloy cathode.

2.3.2 BASIC BATTERY PROPERTIES

Battery capacity is defined by the amount of charge it can deliver to an external consumer. Internal resistance in the battery causes thermal losses, both when charging and discharging the battery. In general, the rated capacity is measured as net charge after thermal losses. With increasing load current, the thermal losses will increase with a rate exponential to the current increase. Therefore, the actual battery capacity is dependent of the load current and defined by Peukert's law and a Peukert constant representing this exponential relation.

$$C_p = I^k \cdot t \qquad (1)$$

C_p is the battery capacity, adjusted for the load current I, to the power of the peukert kostnant, k. t denotes the time of which the load current is drawn. The Peukert constant for Lithium Nickel Manganese Cobalt Oxide (or NMC) cathode varies between 1.05 and 1.08. Different types of cathode alloys give different Peukert constants. For comparison, a lead-acid battery has a Peukert constant of 1.25 to 1.45 (Omar, et al., 2012). The low Peukert constant, minimize the capacity difference between high and low load currents, and makes calculations of the battery state of charge more accurate.

Designing mobile equipment, weight and volume of the energy storage becomes more important. This introduces the terms energy density and specific energy, referring to the amount of energy stored per volume or mass. Lithium Ion Batteries today has a typical energy density of 2.2MJoule/dm^3 and a specific energy of 0.8MJoule/kg. This makes it the most preferable, commercial available, rechargeable battery technology for mobile applications (Zhang, Li, & Zhang, 2017, p. 1).

2.3.3 ELECTRIC EQUIVALENT

Battery cells can be represented precise, as an infinite series of RC-parallels (figure 4 a), or more general by a Thevenin equivalent (figure 4 b). Depending of the purpose of the calculations or simulations, one can choose the equivalent that will fit the need of precision.

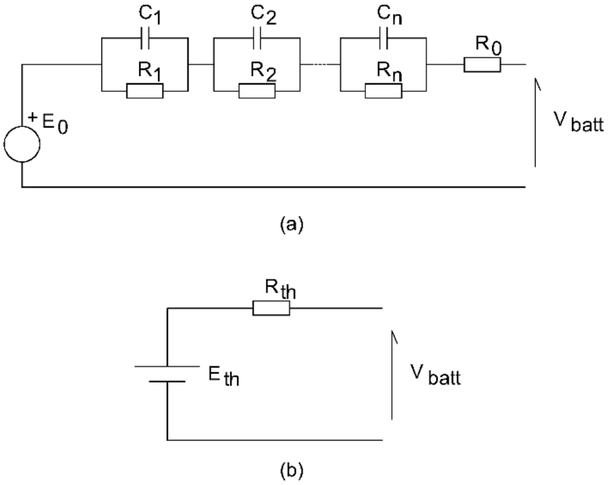


FIGURE 4 – A) RC-PARALLELL SERIES EQUIVALENT, B) THEVENIN EQUIVALENT

In MATLAB Simulink, the PowerSim library contains a generic battery block. This model is based on the precise RC-equivalent of a battery. Correct parametrisation of this battery block requires a list of nine key properties to generate an accurate model. These are:

1. Nominal voltage – lowest terminal voltage in operating range of battery [V]
2. Rated nominal capacity – lowest effective capacity [Ah]
3. Maximum capacity – capacity if used passed nominal voltage, to cut off voltage [Ah]
4. Fully charged voltage – voltage at 100 % SOC, at top of battery exponential zone [V]
5. Nominal discharge current – The current of which the discharge curve is derived [A]
6. Internal resistance – Given impedance at 1000 Hz, fully charged [Ω]
7. Nominal capacity – Capacity discharged from fully charged voltage to nominal voltage [Ah]
8. Exponential zone voltage – The voltage at which the exponential zone is finished [V]
9. Exponential zone capacity – Capacity discharged when the exponential zone is finished [Ah]

If one parameter is missing, the generic battery block can be auto tuned by specifying chemical type, nominal voltage and nominal capacity.

2.4 MARINE PROPULSION

In commercial shipping, propulsion force is normally produced by a rotating propeller. A motor sets the propeller into rotation. Conventionally, this motor would be a diesel engine. Through the last ten years, more and more ships are built with electric propulsion motors. Variable frequency drives are used to vary the propeller speed. This gives the propulsion system a higher flexibility and efficiency due to less mechanical transfer losses and that the operating speed of the diesel engine is independent of the propeller speed.

The propeller main purpose is to convert the applied torque to a forward thrust force. Its performance varies as i.e. the hull disturbs the water or as the propeller rotation sets the tail wake into spin. Observing the propeller in open waters, without the hull interference, the efficiency can be defined by the ratio in equation 2 (Molland, 2008, p. 235).

$$\eta_0 = \frac{THP}{DHP} = \frac{V_a \cdot F_{prop}}{\omega \cdot \tau_{el}} = \frac{K_T \cdot J}{K_Q \cdot 2\pi} \qquad (2)$$

Where η_0 is the propeller efficiency, THP is thrust horsepower and DHP is delivered horsepower from the propulsion engine. V_a is the vessel speed of advance, τ_{el} is the torque applied by an electrical propulsion motor, F_{prop} is the propulsive force and ω is the mechanical angular velocity at which the propeller rotates. The K_Q, K_T versus J characteristic curves contain all the information necessary to define the propeller performance at a steady state operating condition. Indeed, the curves can be used to model the performance of a specific propeller. This, however is a cumbersome process. In the end, the results will only be valid for open water conditions, meaning without the interference from the wake of the hull. Therefore, in ship design, general efficiency tables and rules of thumb are used (Molland, 2008).

Regarding the dynamic properties of the hull, the water resistance can be calculated in many ways. In comparison with physical experiments, calculations often leave a remainder, which represents a mix of resistance data the calculation somehow fail to consider. An open water towing test is the most accurate method to determine the hull water resistance. This test will result in a curve displaying the relation between vessel speed of advance and water resistance. If a ship designer uses the same type of hull for several different ships, the hull open water test curve from the first hull is used to assist the design process of the next one (Molland, Turnock & Hudson, 2011).

2.5 ENERGY MANAGEMENT SYSTEMS

Maritime energy management systems (EMS) main purpose is to ration the use of energy to a minimum. More exact the system will route the energy in the most efficient way possible. In a combustion motor-based power system, the system does so by controlling the main energy consumer’s runtime, and by controlling the number of power production units running. Balancing production up against a planned consumption keeps the standby power as low as possible.

For an all-electric battery vessel, there will be little or no on-board electric production. The EMS’s purpose is then to keep the energy consumption as low as possible and thereby make the stored energy in the battery last for as long as possible. Secondary to this, the EMS system is to manage the transition between one set of system settings to another when the vessel operation mode is changed. A pre-set parameter list defines each setting or mode. The power converters receive the parameter list for the new mode and the parameters change in a specific order to manage a smooth transition between modes.

Further the EMS must manage any irregularities that might occur, in a most efficient way. Faulty conditions in any of the connected components should result in a defined action. The action can in one instant be a message to the operator regarding motor temperature, in another the voltage on the DC-bus is unstable and the action might be to automatically respond with a new set of parameters for voltage control.

2.6 MARITIME SHIP CLASSIFICATION AND REGULATIONS

The development of regulations for ships and maritime labour started when RMS Titanic sank in 1912 and the first convention of safety for the life at sea (SOLAS) was made. Since then, multiple conventions have come to place. SOLAS, MARPOL, LOADLINE, STCW, ISM and ISPS are all maritime conventions that defines standard regulations for ship operation and construction. Every ship nation, or more accurate flag state, ratify these conventions and make them as part of their maritime law. The International Maritime Organization organize these ratifications. In Norway, enforcement of these regulations is carried out by the Norwegian Maritime Directorate. Class societies like Lloyd's or DNV GL is third parties that, amongst other services, define standards and procedures to fulfil the conventions. In Norway, regulations for maritime electrical systems is summarized by the Norwegian Electrical Committee in the norm set NEK 410.

Standards and regulations for using batteries as the one and only energy storage in ships, is yet to be published. As of today, DNV GL has published a handbook for maritime and offshore battery systems and a guide to use batteries in shipping. Further they are revising their "rules for ship classification", part 6, chapter 2: Propulsion, power generation and auxiliary systems. The new version is expected to contain defined regulations for propulsion of ships with batteries as their only energy source (DNV GL, 2017).

3 SIMULINK MODEL

3.1 MODEL DESIGN

3.1.1 OVERVIEW

Using a model for system design purpose and dimensioning, one need to start defining the variables. This model is developed to assist the process of determining the adequate battery capacity for a defined operating range and time. It is also meant as a tool to determine how changes in loads and operating patterns will affect the capacity.

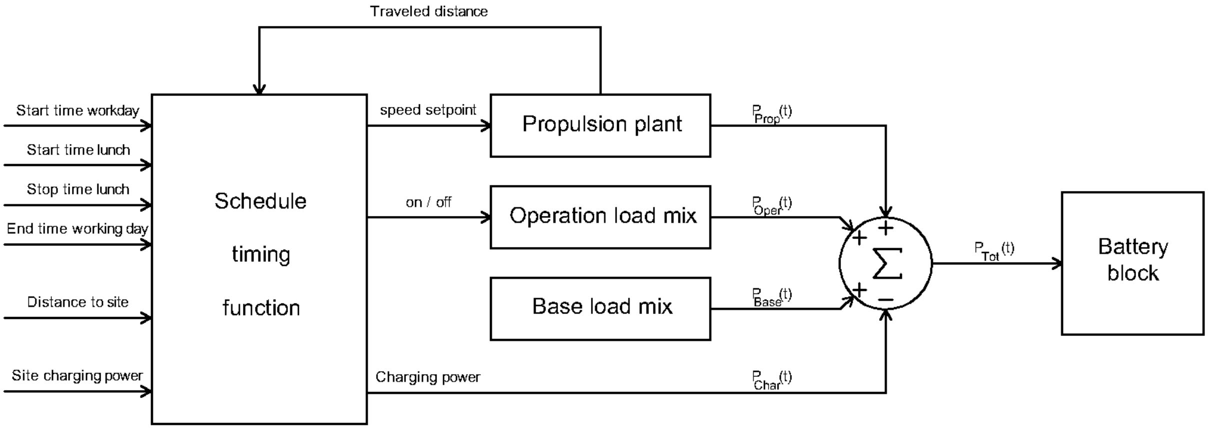


FIGURE 5 – OVERVIEW OF THE MODEL

Figure 5 displays an overview of the main blocks in the model. A schedule function will handle the sequential changes through a workday. Depending on the schedule times, distance to site and the available charging power at site, the schedule function will activate the propulsion plant, the operation load mix or the charger. Loads that are continuously present through the entire workday is represented as the base load. This is i.e. heat, navigation systems or the power supply to the battery management system (BMS).

The continuous sum of all power is transferred to the battery block. This sum represents the net sum of power flowing into or from the battery package. Propulsion is activated from the schedule function by transferring a positive setpoint for rotational speed. A feedback from the propulsion plant to the schedule function will reset the setpoint to zero when the vessel has travelled a distance equal to the defined distance to site.

3.1.2 PROPULSION PLANT

Figure 6 shows the principal of the propulsion plant. The plant is modelled by two second order differential equations (5 and 6), a black box interpretation of the propeller and a hull towing resistance function. The hull towing resistance is estimated by a curve fit operation based on the green resistance curve in Appendix 2. The resulting hull resistance function is presented in equation 3a and 3b.

$$V_a \leq 1{,}31 \qquad \rightarrow \qquad R_{(V_a)} = 265 \cdot V_a \qquad \text{(3a)}$$

$$V_a > 1{,}31 \qquad \rightarrow \qquad R_{(V_a)} = 189 - 1670 \cdot V_a + 1420 \cdot {V_a}^2 \qquad \text{(3b)}$$

The propeller curve relation is based on estimates of the final vessel speed of advance given by GMV and the assumption that the propeller will reach approximately one third of its full angular velocity when it is anchored to a fixed position. The estimated propeller function is presented in equation 4.

$$\tau_{prop} = \sqrt{(1{,}55 \cdot \omega - 12 \cdot V_a)^2} \qquad \text{(4)}$$

In equations 3a, 3b and 4, V_a is the vessel speed of advance, $R_{(V_a)}$ is the hull towing resistance, ω is the mechanical angular velocity and τ_{prop} is the propeller load torque acting on the rotational system.

A model of an internal permanent magnet synchronous machine (presented in section 3.1.5) is the driving element in the propulsion plant.

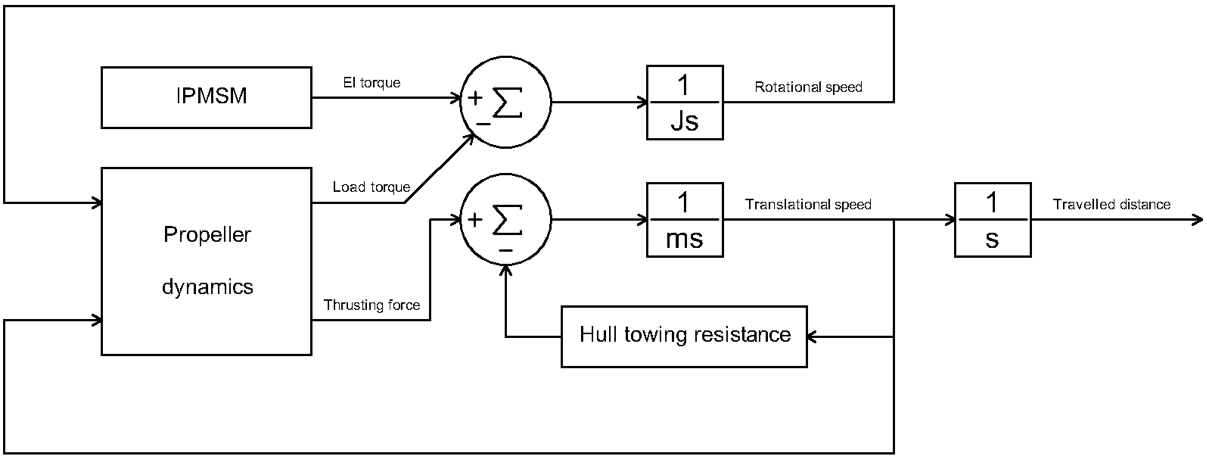


FIGURE 6 – PRINCIPAL SKETCH OF THE PROPULSION PLANT BLOCK

If a drive torque, greater than the load torque, is applied by the IPMSM, the rotational speed will increase. The load torque and the generated thrusting force is dependent of the propeller speed and the vessel speed of advance, at the same time. Two time constants are significant in the system. One for the rotational system and one for the translational system. Response to changes in the rotational speed will depend upon the total inertia in rotating parts, while the response to changes in translational speed will depend upon the total mass of the vessel. In the model, translational speed is integrated in time to obtain the vessel travelled distance. This distance is also fed back to the schedule timing fnction.

3.1.3 ROTATIONAL DYNAMICS

The rotating body consist of rotor, shaft and propeller. Gearless propulsion, and the short shaft to the propeller result in a relative low total moment of inertia for the system of approximately 15 kg/m^2. An IMPSM motor generates driving torque, and the propeller applies load torque to the system depending on the vessel advance speed and the propeller rotation speed. The rotational physics can be represented by a differential equation. Based on Newton’s second law, one has:

$$\mathrm{J}\frac{d\,\omega}{dt} + D_d\omega = \tau_{el} - \tau_{prop} \qquad (5)$$

Where J is the total system inertia, D_d is viscous damping constant representing the friction elements in bearings, and ω is the rotational speed of the system. τ_{el} represents the torque produced by the IPMSM, and τ_{prop} is the load torque produced by the propeller. The load torque is a function of both vessel advance speed and rotational speed.

In figure 6, the net sum of torques are fed through a damper less rotation system. Rotational friction losses are neglected in the model. The torque sum block in the model represents the right side of equation 5. Integration and division by J, the rotation system output is mechanical angular velocity, and as the shaft is gearless, consequently this is also propeller rotational speed ω.

3.1.4 TRANSLATIONAL DYNAMICS

Translationally, the vessel is a body with mass, moving through a fluid. A thrust force is generated by the propeller. As the body increase its translational speed, the water resistance increases exponentially. The system can be represented with Newtons second law:

$$m\frac{d\,v_a}{dt} + R_{(v_a)} = F_{thrust} \qquad (6)$$

Where m is the vessel mass of approximately 28000 kg, v_a its speed of advance, F_{thrust} is the thrust force generated by the propeller and $R_{(v_a)}$ represents the hull water resistance. Thrust force generated by the propeller is a function of both vessel speed of advance and propeller rotational speed.

3.1.5 IPMSM

Based on the assumption that the interior permanent magnets create a sinusoidal distributed field, that the conductor distribution in the stator is sinusoidal, the IPMSM can be modelled in the d-q reference frame like a DC-machine. There is also no airgap loss in the model. Fixating the d-axis along the field axis of the permanent magnets makes the reference frame stationary to the rotor position, regardless of speed. Figure 7 shows the created model of the IPMSM.

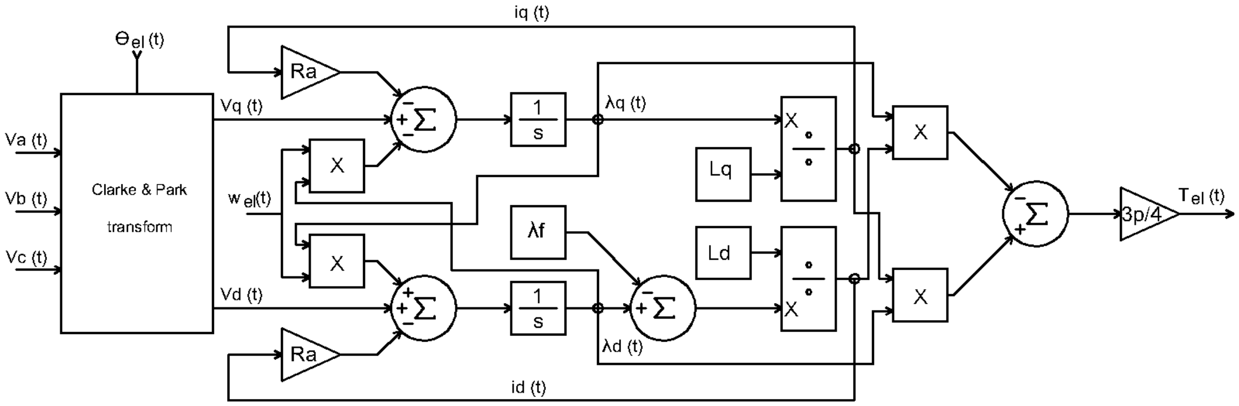


FIGURE 7 - REALIZATION OF AN IPMSM MOTOR IN SIMULINK

A Clarke/Park transform calculates the d-q voltages from the motor terminal voltages v_a, v_b and v_c, using the rotor electrical position as input. The rotor electrical angular speed ω_{el} is feed into the model to calculate the back EMF. Reading from left to right, the model is constructed from the IPMSM equations for voltage, flux linkage and torque generation (7 to 11).

From the d-q voltage equations (7 and 8), one has:

$$v_q(t) = R_a \cdot i_q(t) + \frac{d\,\lambda_q}{dt} + \omega_{el}(t) \cdot \lambda_d(t) \;\rightarrow\; \lambda_q(t) = \int (v_q(t) - R_a \cdot i_q(t) - \omega_{el}(t) \cdot \lambda_d(t))dt \qquad (7)$$

$$v_d(t) = R_a \cdot i_d(t) + \frac{d\,\lambda_d}{dt} - \omega_{el}(t) \cdot \lambda_q(t) \;\rightarrow\; \lambda_d(t) = \int (v_d(t) - R_a \cdot i_d(t) + \omega_{el}(t) \cdot \lambda_q(t))dt \qquad (8)$$

From the d-q flux linkage equations (9 and 10), one has:

$$\lambda_q(t) = L_q \cdot i_q(t) \;\rightarrow\; i_q(t) = \frac{\lambda_q(t)}{L_q} \quad (9)$$

$$\lambda_d(t) = L_d \cdot i_d(t) + \lambda_f \;\rightarrow\; i_d(t) = \frac{\lambda_d(t) - \lambda_f}{L_d} \quad (10)$$

And finally, the torque generation is given by the IPMSM d-q torque equation (11):

$$\tau_{el}(t) = \frac{3 \cdot p}{4} \cdot (\lambda_d \cdot i_q(t) - \lambda_q \cdot i_d(t)) \qquad (11)$$

In the equations (7 to 11) v_q, v_d, i_q, i_d, L_q and L_d are the q and q axes stator voltages, currents and inductances respectively. R_a is the stator resistance and λ_f is the amplitude of the permanent magnet flux linkage. ω_{el} is the electrical angular velocity in rad/s. p is the number of poles (Haque & Rahman, 2009).

The resulting torque is applied to the rotational system in the propulsion plant. The figure 5 to 7 does not show this, but rotor electrical angle θ_{el} and angular speed ω_{el} is fed back to the IPMSM model from the propulsion plant, scaled by the number of pole pairs. Further the IPMSM model need a working controller to run. This controller is not shown in the model figures, as designing the controller is not considered a part of this thesis.

3.1.6 BATTERY BLOCK

Using the generic battery block in Simulink, the dynamics of the battery performance is modelled. The battery block is from the Simscape library PowerSim, meaning that the connections are simulated as wires with voltage potentials, carrying current. This block is different from the rest of the model, as it requires a conversion between Simulink signal connections and Simscape wire connections. In figure 8, the battery model principal is displayed. Simscape wire connections are indicated with circle connections, and Simulink signal flow is indicated with arrows.

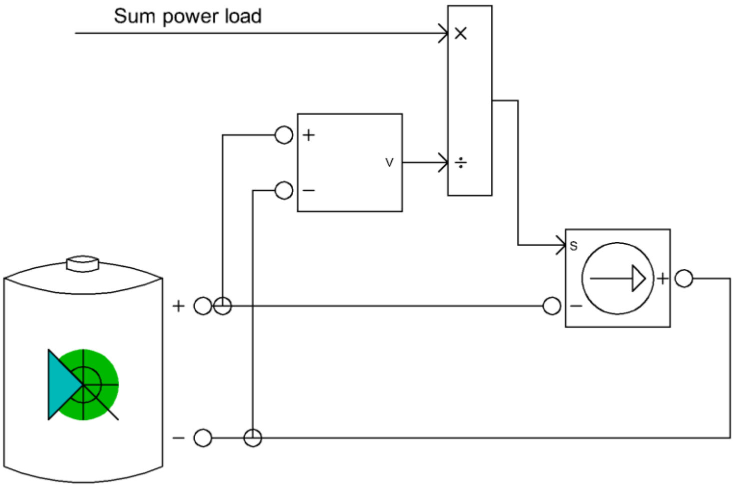


FIGURE 8 - BATTERY BLOCK CREATION

All loads in the vessel is connected to the source through a converter via the 600 V DC bus. The battery will be connected to the DC bus through a DC/DC converter. Seen from the battery, the load will act as an ideally stiff load in normal operating condition. The power consumption will be constant, regardless for the voltage at the battery terminals. In figure 8 one sees that the Simulink input from the external model divided by the battery terminal voltage gives the load current. This is done by using a voltmeter and a controlled ideal current source. This model will only be true for a defined voltage range. Maximum charge and discharge current ratings for the battery and the current limitation are obvious limits for this load stiffness, but as the battery on this vessel only operates between 20 and 90 % SOC it stays true for normal operating conditions. Adding the thermal physics of the surrounding environment, the generic battery block can estimate cell temperature. This feature is not adapted in this model, but it is possible to expand the complexity as the model is tuned to real data.

3.1.7 EFFICIENCIES

Running the propulsion plant, the power drawn from the batteries might be very different from the power finally moving the ship forward. The efficiency of each component in the supply chain is illustrated with a Sankey diagram in figure 9.

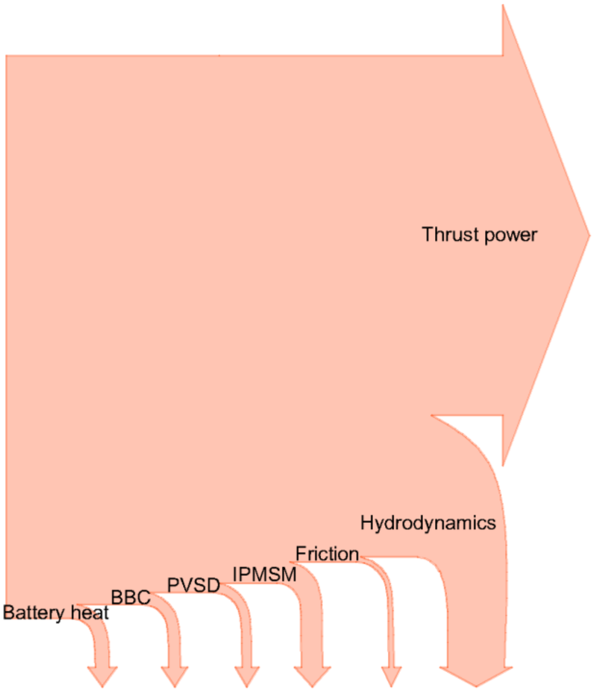


FIGURE 9 - SANKEY DIAGRAM OF POWERFLOW FOR PROPUSION

The diagram shows losses as arrows pointing down, and effective propulsive thrust power as an arrow pointing right. This Sankey diagram is a representation of the following efficiencies:

Battery discharge efficiency, $\eta_{batt} = 0.98$

Buck boost converter efficiency, $\eta_{BBC} = 0.98$

Propulsion variable speed drive efficiency, $\eta_{PVSD} = 0.98$

Internal permanent magnet synchronous machine efficiency, $\eta_{IPMSM} = 0.96$

Rotational transmission efficiency, $\eta_{friction} = 0.99$

Propeller efficiency, $\eta_{propeller} \approx 0.70$

The Sankey diagram illustrates that hydrodynamic performance of the hull and propeller represents a large part of the losses. It is too large to make usable estimates of the vessel energy consumption without data from the vessel in operation.

3.2 TUNING GUIDE

To adjust the physical parameter in the model to match real parameters in the vessel system, the model need to be tuned towards some criterion of convergence. This chapter will present a suggested approach to such tuning.

3.2.1 HULL WATER RESISTANCE

Towing the vessel through open waters, while measuring the force acting on the towing rope and the vessel speed, will give a representative resistance curve for this hull. The dataset is then fed through a regression or curve-fit program i.e. Simulink curve fit add-on. The result is an approximate polynomial expression for the hull water resistance. This expression reads the ratio between propulsive force and vessel speed at all recorded speeds.

3.2.2 BLACK BOX TECHNIQUE

Dynamic simulation of hydrodynamics and the forces acting on the propeller is very complex. Accurate knowledge of the propeller performance is essential to be able to estimate the energy consumption on the vessel. For this model, there are two important relations. First how large a propulsive force is created per torque applied to the propeller shaft. Second is how does this relation change as the vessel is coming up to speed. In the model, the applied torque is fed through a dynamic model of the rotational system (figure 6) and the resulting rotational speed is the output. The propulsive force is fed to the translational system (figure 6).

To estimate the propeller load function in the model it is possible to create a black box system with inputs and outputs that are equivalent to parameters that can be measured and logged during sea trial. At a given vessel speed of advance and a given rotational velocity, the load torque and the propulsive force is given. This applies only if the propeller efficiency η_0 is constant for all values of vessel speed and propeller angular velocity. This vessel will operate at low speeds and the propeller angular velocity is relative low. The assumption that the propeller efficiency is constant in the operating range of this system holds.

A sketch of the black box function is displayed in figure 10. The inputs and outputs are parameters that can be logged during the vessel sea trial. Feeding the dataset through a solver i.e. in MATLAB will result in satisfactory estimates of this relation.

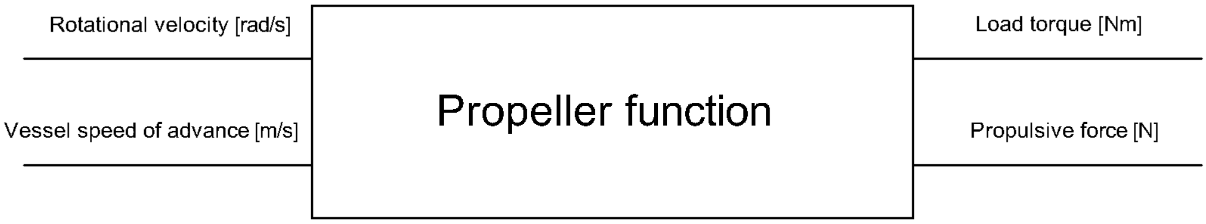


FIGURE 10 - BLACK BOX FUNCTION FOR PROPELLER PERFORMANCE

3.2.3 LOAD MIX INPUT

Simulating the load mix without data of how the different operations performed on board affect the energy consumption makes little sense. While testing the vessel, the load for heating, hydraulics and equipment connected through the 230V grid can be recorded. Data on energy usage for a wide range of operations will be input for the load mix block in the model. The load mix block is prepared to simulate a mix of continuous, slow varying and intermittent loads simultaneously.

3.2.4 BATTERY PARAMETERS

To obtain the relevant battery parameters without the ones that is kept secret by Corvus, it is possible to log the battery terminal voltage and the battery current over time. From a dataset of these two values, logged through a wide range of operations, one can derive an equivalent for the battery that will be sufficient for accurate simulations in MATLAB. The MATLAB model of the battery already gives adequate accuracy regarding capacity, but it lacks precision regarding the internal resistance. The internal resistance is relevant if the model shall produce detailed information on the battery terminal voltage.

3.3 MODEL TEST

3.3.1 MODEL INPUT DATA

In this test, the data for the battery is based on a standard generic battery model in MATLAB. Total battery capacity is set to 700 Ah, battery nominal voltage is set to 510 V and the battery response time is set to 30 s. MATLABs automatic parametrisation of the lithium battery results in an internal resistance of 7,29 mΩ and a nominal drain current of 304 A. This estimate is based on characteristics of Lithium based batteries in general, not on Lithium NMC chemistry specifically. It is assumed that the general estimated internal resistance is higher than the actual NMC value, and that the real nominal drain current is higher than the estimate. The propeller function is an estimate based on GMV's assumption that the vessel will reach a speed of advance of 9 knots at full propulsion power at 600 rpm. Further the overall efficiency of the propulsion system is defined as sketched in figure 9. Load mix is set to constant 6 kW and the base load including heat is set to constant 4 kW. This is based on GMV's assumptions on average loading. Normally these loads will be partial intermittent, but in this test, they are represented as a constant energy consumption. Hull water resistance is modelled by a simplified third order curve fit (3a and 3b) of a resistance curve for similar hull types, provided by GMV. Simulation time is set to eight hours. This is meant to represent a normal working day. The programmed schedule is shown in table 1.

TABLE 1 - SCHEDULE FOR TEST SIMULATION

Start time work day	08:00
Start time lunch	11:00
End time lunch	11:30
End time work day	16:00
Distance to site	5 nautical miles (9260m)
Site charging power	140kW

The model is set to change the propulsion plant propeller speed setpoint to 600 rpm at 08:00, and change this to zero when the vessel has travelled 5 nautical miles. Arriving at site will initiate the load mix. At lunch, the load mix stops and charging is performed at the specified power of 140 kW. After lunch, the charging stops and the load mix is again initiated. When there is only enough time for the return journey, the load mix stops and setpoint for propeller speed changes to 600 rpm. The model runs until the specified distance is elapsed. Heating power is constantly on during the entire workday.

3.3.2 SIMULATION RESULT

The plot in figure 11-15 is divided into five parts where the first (A) and the last (E) represents cruise mode. This is the parts where the vessel travels to and from site at full propulsion power. Part two (B) and four (D) represents operation mode. This is the parts where the vessel is performing operations on site. The middle part (C) is representing charge mode, where the batteries charges during lunch time.

The time in the plots starts counting hours from zero at the defined start of the working day.

The vessels travelled distance is displayed in figure 11.

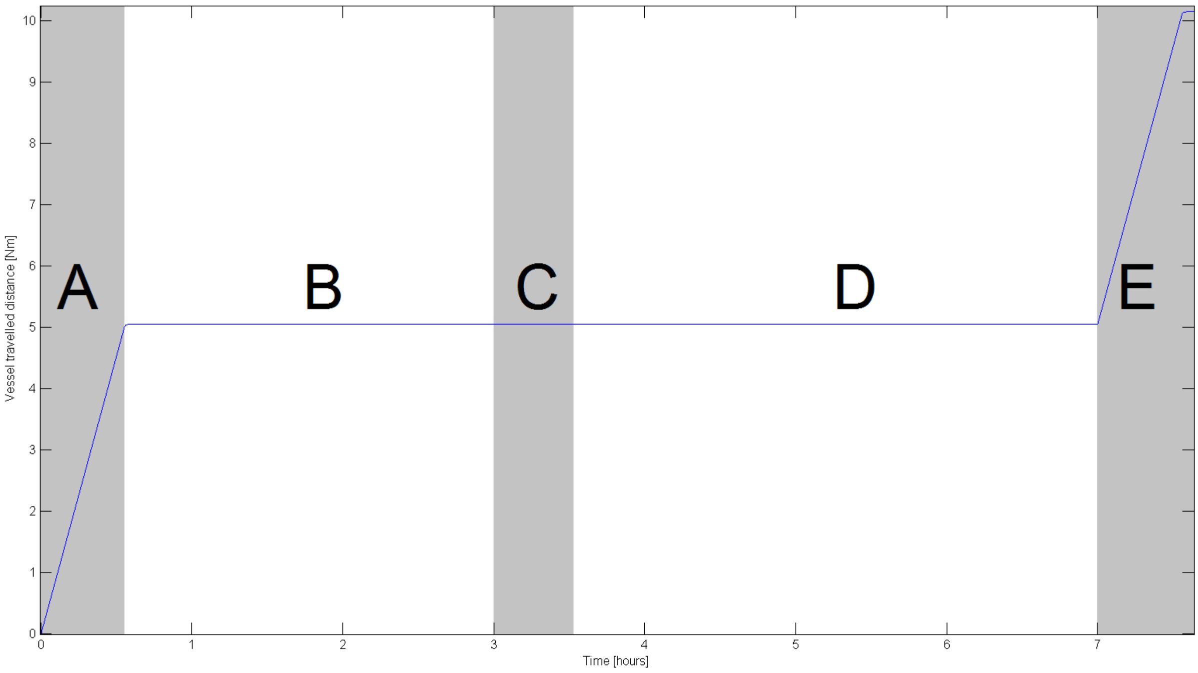


FIGURE 11 - PLOT, VESSEL TRAVELLED DISTANCE

Figure 11 shows that the vessel travels ten nautical miles in two portions. First five on its way from shore to site, remaining five on its return. The vessel will use its propulsion plant to move around the fish farm in operation mode (B and D). This positioning movements is seldom at full propulsion power and the travel distance is low compared to the distance to site. Therefore, it is not included in this simulation test. It will be possible to include all use of the propulsion plant in the simulation as the sea trial provides data on this load pattern.

The battery SOC is displayed in figure 12.

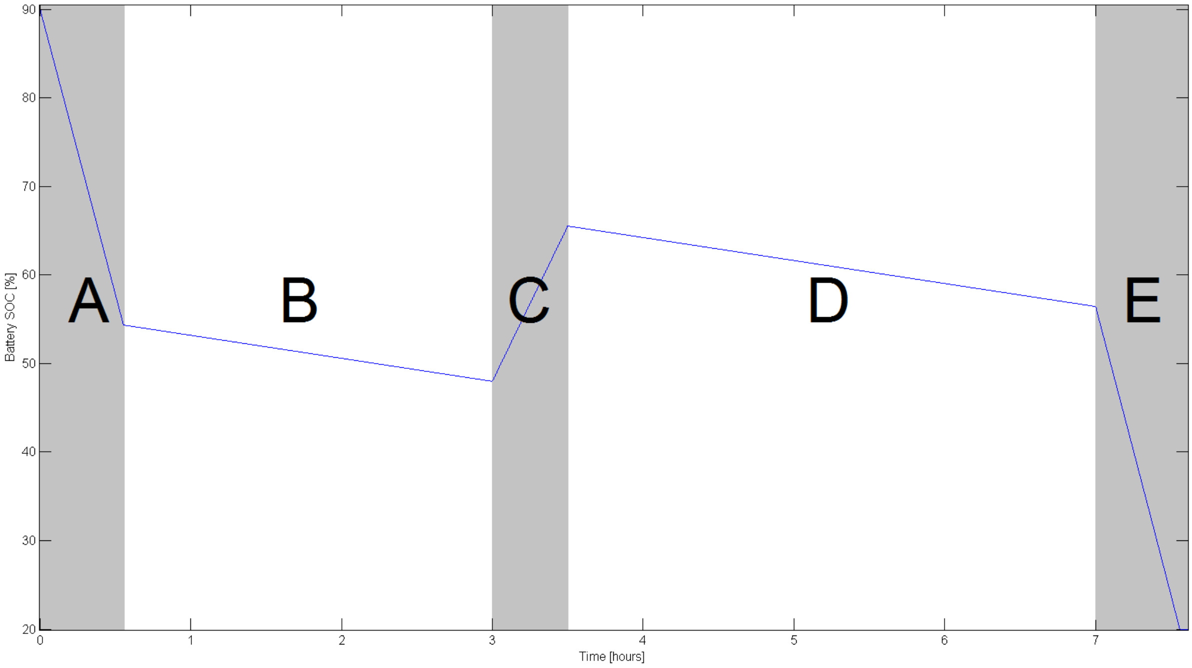


FIGURE 12 - PLOT, BATTERY SOC

Ideal operating range for the batteries is between 20 and 90 % SOC. As displayed in figure 12, the initial battery SOC is set to 90 %. This corresponds to the battery’s ideal operating range. During the journey to site (part A) the battery SOC reduces with 37 %. This is approximately the same for the return journey (part E). Half an hour charging during lunch time (part C) lifts battery SOC by 15 %. During the operation mode (part B and D) the SOC drops at a lower rate, and figure 12 shows that the charging supplies more energy to the batteries than used during the operation mode.

The battery current is displayed in figure 13.

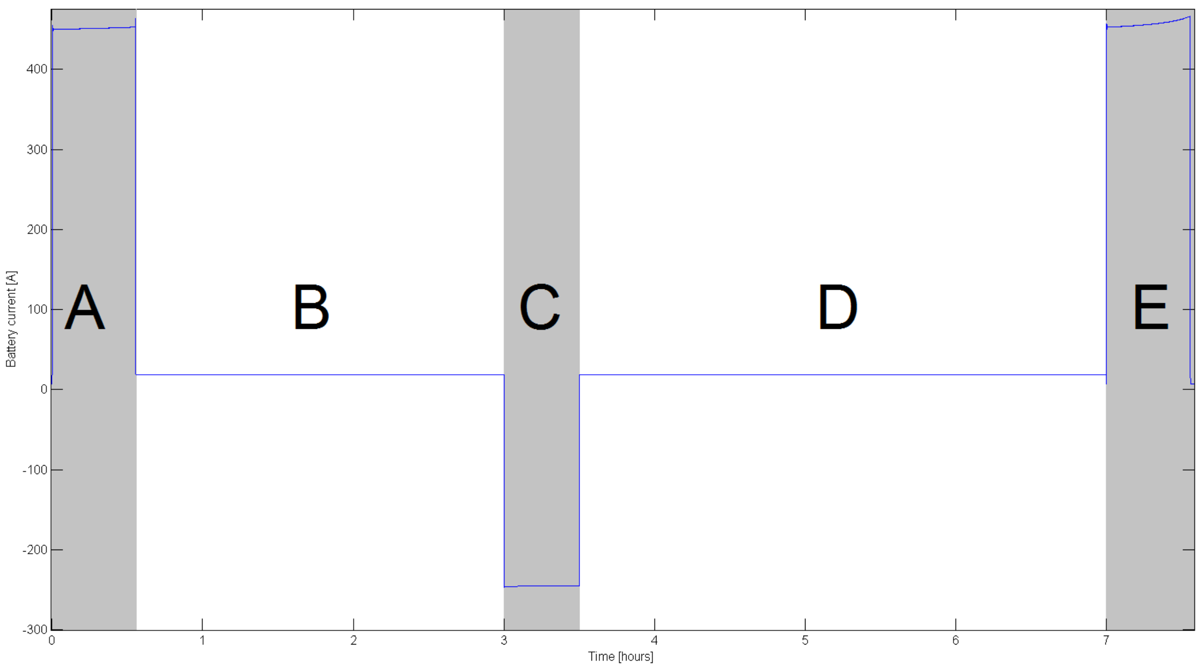


FIGURE 13 - PLOT, BATTERY CURRENT

Loading the batteries result in positive battery current. Charging the batteries result in negative battery current. Positive direction means current flowing from the batteries. Figure 13 shows that the load current is approximately 450 A during the journey to site (part A). This is when the vessel operates in cruise mode, and the propulsion plant is running at full power. The same loading is applied for the return journey (part E), but the graph shows a distinguishable increased load current as the battery SOC gets lower. This happens as the battery terminal voltage get lower and the load stays constant. The BBC current limit on the battery side is 544 A, so the current margin is still acceptable.

The battery voltage is displayed in figure 14.

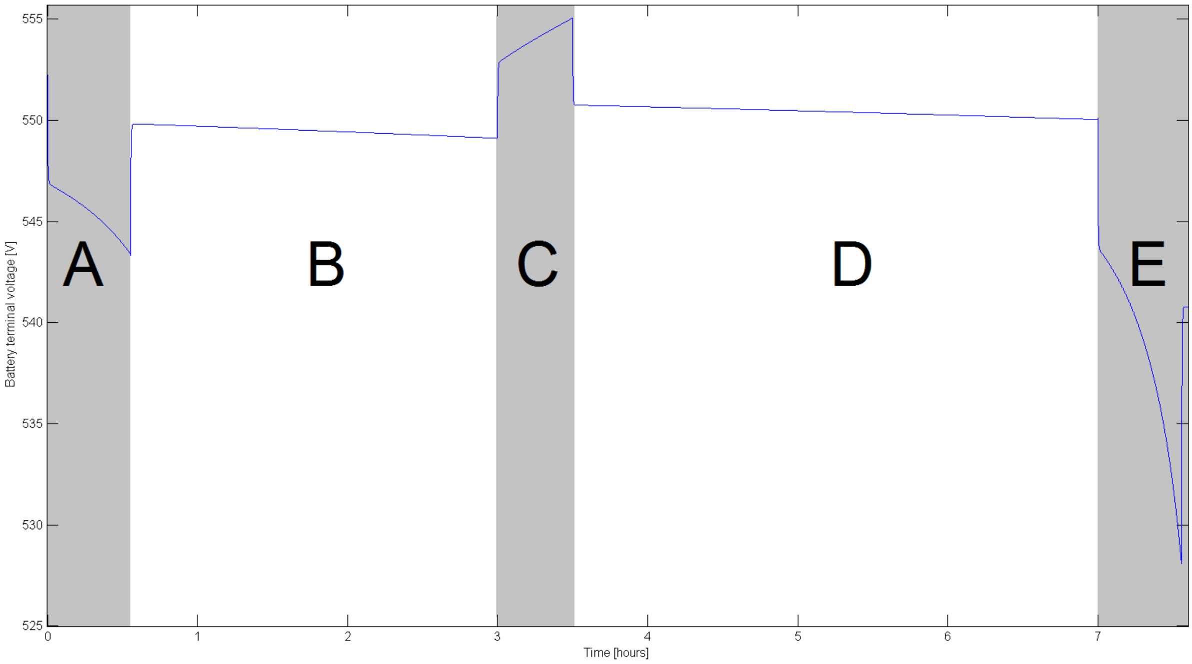


FIGURE 14 - PLOT, BATTERY TERMINAL VOLTAGE

The battery terminal voltage is a part of the simulation that strongly depends on the defined internal resistance. This model is based on the automatic calculated internal resistance in MATLAB. In general, the curve shape in figure 14 will be recognizable for typical lithium chemistry batteries, but the range over which the voltage vary in the plot may be very different from the real range. Figure 14 shows the highest battery terminal voltage at the end of the charging (part C) and the lowest battery terminal voltage on the return journey (part E). This is plausible as battery terminal voltage decrease when the SOC gets lower. The data from the return journey is in part E. As the vessel reaches its destination, the propulsion plant rpm setpoint changes from 600 rpm to 0 rpm. The load current changes from full to almost zero. This leads to a sudden voltage rise on the battery terminal as the voltage drop over the internal decrease to near zero volts.

Cumulative battery capacity usage is displayed in figure 15.

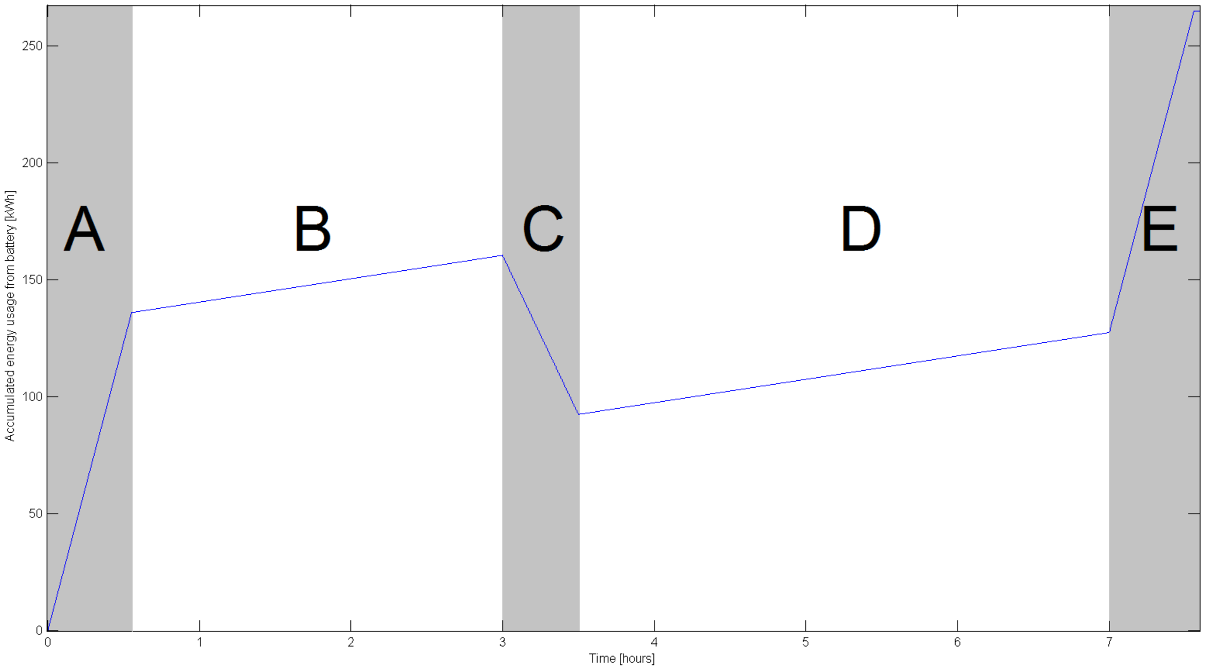


FIGURE 15 - PLOT, CUMULATIVE BATTERY CAPACITY USAGE

For vessel design purpose, perhaps figure 15 shows the most interesting curve. The cumulative capacity usage represents the net amount of energy the vessel has drawn from the batteries during one working day. The more energy is fed to the batteries during charging (part C), the less battery capacity the vessel will need. This simulation result in a total net energy of 265 kWh, drawn from the batteries. In practice, it means that a battery capacity of 265 kWh is sufficient for the load profile in this simulation.

3.3.3 CRITERION OF CONVERGENCE

Before the simulation model is suitable for design purpose, the model need to be tuned according to the tuning guide in section 2.3. After inital tuning, recorded data from a working day can be set up in the schedule of the model. Comparing the simulation result with recorded data from the test will result in some error.

There can be many explanations for this error. Weather, sea margin and coastal currents might affect the vessel test result, but not the simulation. Heavy weather can be recorded in comments to the testing, but fouling on the hull and propeller is difficult to compensate for in the model.

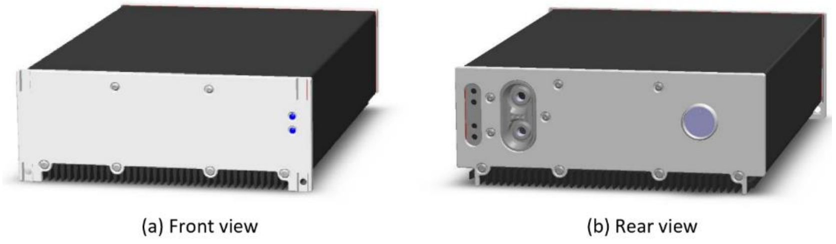
There must be a convergence criterion to when the model is considered accurate enough. It seems reasonable that the normal estimates for weather and sea margin in shipping can be used as a criterion for convergence. When the recorded energy usage from the test, repeatedly is less than 5 % different from the simulation result, the model is considered suitable for design purpose.

4 EMS FUNCTIONAL SPECIFICATION

4.1 COMPONENT DESCRIPTION

4.1.1 BATTERY DATA

The battery package is supplied by Corvus Energy. It’s built from modules. Each module has a nominal voltage of 50,4 V and a nominal capacity of 5,7 kWh. Figure 16 shows a typical battery module.


(a) Front view

(b) Rear view

FIGURE 16 - CORVUS BATTERY MODULE

One battery string is a series connection of 11 modules, resulting in a nominal string voltage of 554,4 V. A total of five strings is installed in the vessel. Two strings are mounted in a rack located in the port side hull, the last three is mounted in another rack located in the starboard side hull. Each rack has a master control module. This module will handle all communication between the modules and the BMS. Figure 17 shows a rack, housing two parallel strings with 11 modules in series. The master control module is located at the bottom of the rack on the left side. Main connections and cooling fans is placed at the base of the rack.

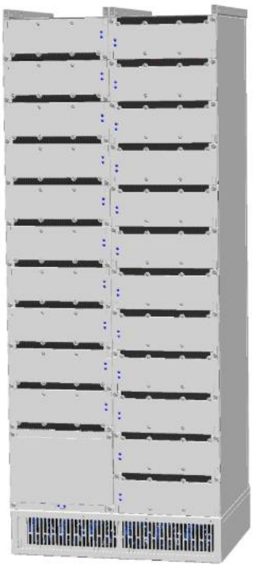


FIGURE 17 - BATTERY RACK CONTAINING TWO STRINGS

For dynamic modeling purposes, one will make use of several characteristic parameters of a battery, such as internal resistance, capacitance chain, etc. For this description, there are only three relevant parameters: capacity, voltage range and current range. The same state of charge will result in different voltages on the battery terminals, depending on the battery load current. This is because of the internal resistance in the batteries. As the battery producer did not provide the details for the internal resistance, these limits are based on estimated by the Simulink generic battery model.

Battery lifetime is often measured in no of deep discharge cycles. Corvus' batteries are expected to have a lifetime of 8000 cycles if the SOC never is below 20 % or above 90 %. The nominal energy capacity of the battery package is 340 kWh. Keeping SOC between 90 and 20 % SOC will allow the vessel to consume approximately 238 kWh from the battery package. Total available energy consumption for one working day will also depend on the onsite charging. Any additional charging in lunch time at sea, will increase the available energy.

If the batteries are operated in this range of SOC, the terminal voltage on the batteries will have its maximum voltage potential at 90 % SOC with no load. Minimum terminal voltage occurs at 20 % SOC with full load current. The maximum continuous discharge current from the battery pack is given to be significantly higjer than the BBC can carry to the DC bus. Based on the lowest terminal voltage and the maximum current in the BBC (referred the battery side), the maximum power limit is given to be 260 kW. This limit is based on the worst case, meaning at the lowest battery terminal voltage. In most operating conditions, the terminal voltage on the batteries will vary between 480 V and 550 V. In the converter setup, the limit is set by a maximum current parameter. Consequently, the real power limit will be a dynamic function of the battery terminal voltage. At the best, meaning high battery terminal voltage, maximum current in the BBC allows a power consumption from the batteries of approximately 300 kW.

4.1.2 CONVERTER DATA

All the loads connected to the DC bus is connected through different types of electronic power converters. Their power limit depends on the power circuit components and their ability to carry current without overheating. Therefore, the only relevant converter data for this description is current tolerance, normally specified as one continuous rating and one peak load rating within a defined peak interval. The converters are supplied by Danfoss and the brand is Vacon. The converter current limits are listed in table 2.

TABLE 2 - CONVERTER CURRENT LIMITS, REFERRED DC-BUS SIDE

Converter type	Continuous DC Current [A]	Peak DC Current [A]	Peak current interval [s]
Charging rectifying converter (CRC)	444	488	60
Buck boost converter (BBC)	380	418	60
Static frequency converter (SFC)	25	27	60
Propulsion variable speed drive (PVSD)	300	330	60
Bow thruster variable speed drive (BVSD)	83	91	60
Hydraulic pressure unit drive (HPU)	100	110	60

All ratings in the table are estimates for the DC-bus side of each converter. This is done to ease calculations of limits for the power flow. As the terminal voltage on the batteries vary, the voltage rise through the BBC will change and so will the DC-bus side current limit. The DC bus side current limit for the BBC given in table 2 is based on the lowest possible battery terminal voltage (420 V).

4.1.3 MOTOR DATA

The propulsion motor is a liquid cooled permanent magnet synchronous machine with interior permanent magnets in the rotor. The supplier is Tema Motors and the motor type is LPMR300. Motor nominal ratings are listed in table 3 below. Complete datasheet for the motor can be found in appendix 1.

TABLE 3 - IPMSM NOMINAL RATINGS

Axle power	107 kW @ 600 rpm
Inverter powers supply voltage	470-600 Vdc
Speed	600 rpm
Current	218 A
Power factor	0.77-1.00
Efficiency	96.9 %

The propulsion motor is managed through its PVSD, so that parameters is not directly relevant to the design of the EMS. However, if dynamic limits regarding speed, voltage or current is to be set, one should not exceed the capacity of the motor itself.

4.2 HARDWARE TOPOLOGY

The central power distributing system involved in operation of the ship consists of the following hardware components (supplier make in parentheses):

- Battery pack (Corvus)
- DC-DC converter (Vacon)
- Charger rectifier (Vacon)
- 230V grid static frequency converter (Vacon)
- Propulsion frequency converters (Vacon)
- Thruster frequency converter (Vacon)
- Hydraulic pump frequency converter (Vacon)

Downstream from the 230V grid static frequency converter, there is a miniature circuit breaker (MCB) fuse box. This is not considered a part of the central power distributing components on this vessel and its functionality is therefore not considered in this description.

Figure 18 displays an overview of the hardware topology in the onboard system.

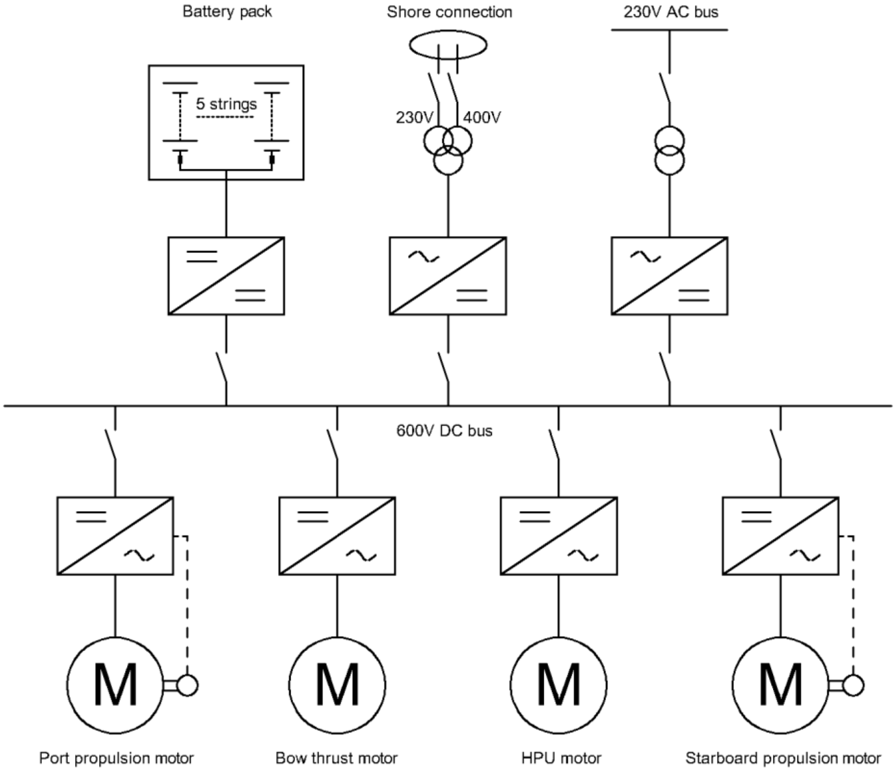


FIGURE 18 - HARDWARE TOPOLOGY

All power consumers and sources are connected to a common 600 V DC bus through electronic power converter. A shore connection feeds through an insulating transformer and a bus connected controlled rectifier, the CRC. Batteries are connected to the DC bus through a buck boost dc converter, the BBC.

4.3 MAIN OPERATING MODES

4.3.1 HARBOURING MODE

When the vessel charges from a stationary source, the vessel operates in harbouring mode. This mode serves both for overnight charging and for charging at the fish farm. Charging overnight will not require any of the on-board consumers to be active, except from the heat exchanger. Cold season operation will involve some pre-heating of the vessel; this should also be possible to set by a timer function. Charging in the fish farm, one will need all control equipment on the bridge to be active, and in some cases, there will be external loads connected to the 230 V distribution. The HPU VSD is normally off and manually activated when needed. Active power components in harbouring mode is displayed in figure 19.

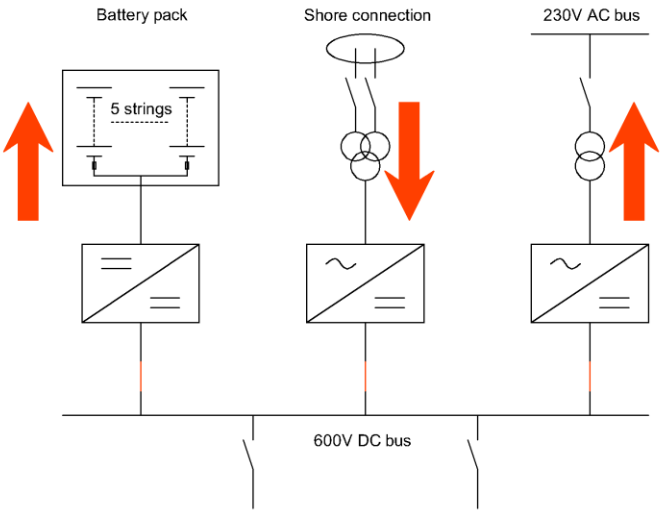


FIGURE 19 - ACTIVE POWER COMPONENTS IN HARBOURING MODE

The CRC is in voltage control, set to control the voltage on the DC bus to 600 V DC. Current is a dependent variable limited to the lowest current tolerance in the power supply chain. Normally the supply chain consists of: Shore feeding point, shore connection cables, insulation transformer and CRC with filter. The lowest capacity in the chain will define the current limit setting in the CRC. Power flow direction is indicated with red arrows.

The BBC is in current control, set to charge the batteries with a pre-set current. If the power drawn by the BBC exceed the power delivered by the CRC to the DC bus, the voltage on the DC bus will start to drop. To avoid this, the current in the BBC should be dynamically limited. If this limit is dependent of the power delivered by the CRC, the potential disturbance from the power consumption of the 230 V grid SFC becomes a problem. The current limit should therefore be dependent of a DC-bus voltage minimum or a calculated net power sum.

4.3.2 CRUISE MODE

Cruise mode is when the vessel travels routine distances between fish farms and base. In cruise mode, all consumers will be active except for the HPU. The HPU runs intermittent trying to maintain the hydraulic pressure in the accumulation tank between minimum and maximum values. Because of some pressure loss over time, from time to time the HPU will fire up, even if there is no hydraulic load consumption. Therefore, the VSD running the HPU shuts off in cruise mode to avoid unnecessary energy consumption. Active components are displayed in figure 20.

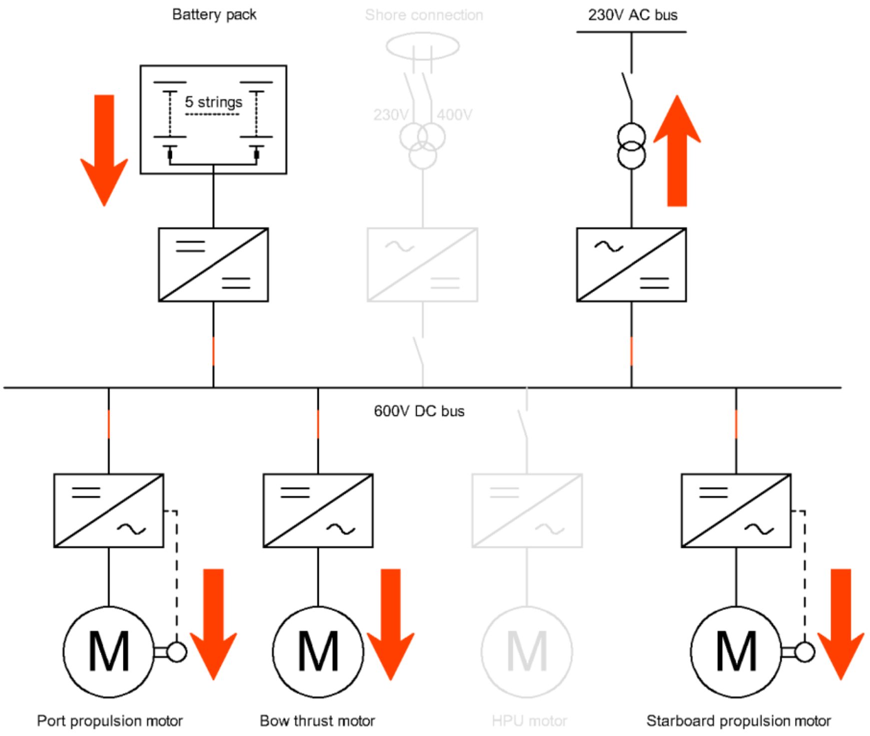


FIGURE 20 - ACTIVE POWER COMPONENTS IN CRUISE MODE

In cruise mode, BBC runs in voltage control, set to maintain constant voltage on the DC bus. Current is a dependent variable, but limited to the batteries or BBC’s maximum discharge current. If the current drawn from the DC bus is greater than the maximum discharge current, the bus voltage will drop. Therefore, all consumer converters should be limited by a constant maximum sum of power (discussed in section 4.5.1). As the SOC gets lower in the batteries, a constant power output requires more battery current. This is significant at the knee of a typical discharge curve for lithium batteries. If the vessel is to be operative at a SOC below the knee, there should be a limit in the discharge current as well. Power flow direction is indicated with red arrows. It is possible to give the operator a calculated available power in the HMI. This way one can always make active choices of how to prioritize available power.

4.3.3 OPERATION MODE

Operational mode is when the vessel has arrived at site and the crew will start the planned operations. Active components are displayed in figure 21. This mode differentiates from the cruise mode in two ways. First, the propulsion VSD's will not be the major power consumer, but remain stand by for positioning operations. Second, the HPU turns on and the intermittent load from the hydraulic pump will be present in the load mix.

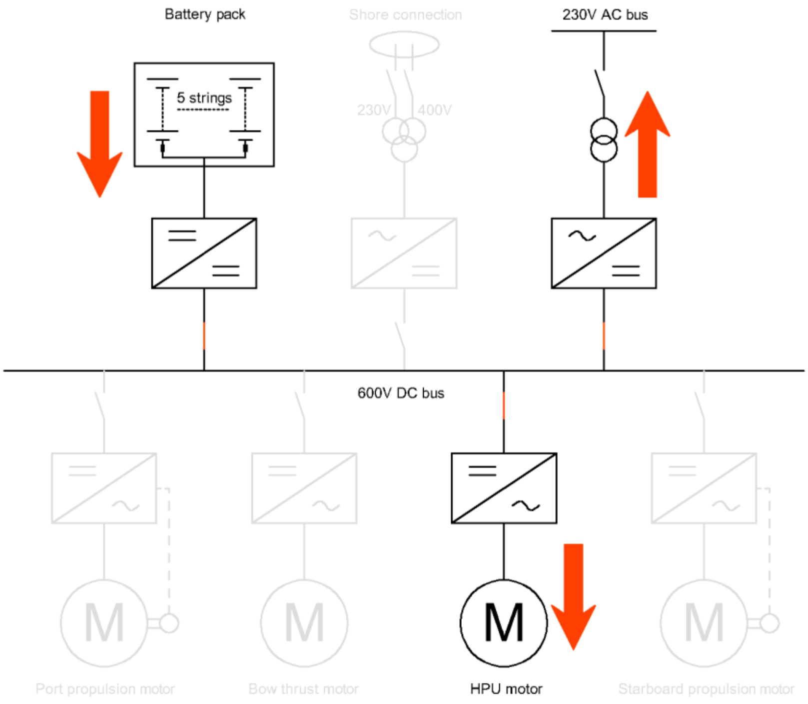


FIGURE 21 - ACTIVE POWER COMPONENTS IN OPERATION MODE

Due to the increase in uncertain load transients, one could argue that the overhead power reserve (discussed later in section 4.5.1) should be increased in this mode. Still, the peak power consumption is significantly lower in this mode compared to the cruise mode. Therefore, the probability that the power consumption, at any time, will exceed the limit of the battery is neglectable. Power flow direction is indicated with red arrows.

A calculated range of movement at a defined vessel speed should be displayed for the operator. This way, it will be possible to consider the energy usage for operation up against i.e. the needed power for the journey back to base.

4.3.4 TRANSIT MODE

In transit mode, the vessel operates as a hybrid electrical vessel. The DC bus is continuously fed by an autonomous on-board generator set through the CRC. Active components are displayed in figure 22.

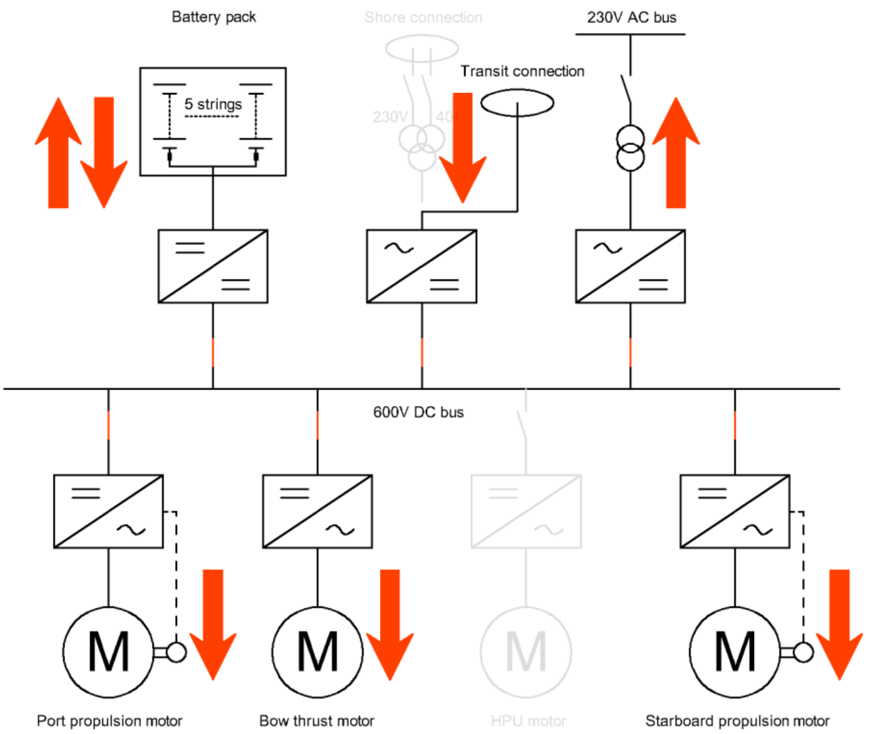


FIGURE 22 - ACTIVE POWER COMPONENTS IN TRANSIT MODE

This is a special case and will not be described in detail in this functional description. Possible power flow direction is indicated with red arrows. If the galvanic separation in the insulation transformer is not needed, the autonomous on-board generator set should feed directly to the CRC to minimize losses.

4.4 STEP BY STEP MODE TRANSITIONS

In mode transitions, there will be a risk of transient voltage instability on the DC bus. With a transient voltage drop, the 230 V grid may fall out of operation. If the BMS loose the 230 V AC supply voltage, the batteries may not remain connected. Bridge equipment crucial to navigation and manoeuvring is also dependent of a constant 230 V supply.

4.4.1 HARBOURING TO CRUISE

Changing between harbouring mode and cruise mode, there is a change in control variables in both the BBC and the CRC. The CRC change from voltage control to no operation and the BBC change from current controlled battery charging to voltage control. This change of variables must take place while the 230 V SFC still is loading the bus. Preferably, there should not be any voltage instabilities during the transition. Mode transition, step by step:

0. Harbouring mode: CRC in voltage control, BBC in current control.
1. BBC ramps down battery charging current to zero.
2. BBC ramps up battery discharge current until CRC current is zero.
3. CRC shuts down and BBC switches to voltage control.
4. On board shore cable switch opens.
5. Open the feeding switch and disconnect shore cables.

4.4.2 CRUISE TO HARBOURING

After the vessel is moored to the quay or to the fish farm, the system need to change parameters to charge the batteries. Mode transition, step by step:

0. Cruising mode: BBC in voltage control, CRC shut down.
1. Connect shore cables.
2. Close the shore feeding switch.
3. Close the on-board shore cable switch.
4. Turn on the CRC and BBC switch to current control.
5. Ramp down the battery discharge current to zero.
6. Ramp up the battery charging current to max charging limit in supply chain.

4.5 EMS CONTROLLED FUNCTIONS

4.5.1 POWER SUM CONTROL AND DYNAMIC CONSTRAINTS

To control the power balance, the EMS can use a sum of power control strategy. Each converter connected to the DC bus has a built in current measurement. These parameters transfer to the EMS through the Modbus communication bus. As the voltage on the DC bus is constant, net sum of power into or out from the bus is easily obtained from the current measurements.

Power sum control serves to maintain power balance. This is done by balancing the current flow into and out from the bus. In situations loading the batteries, balancing means limiting the sum of individual load currents to the maximum current rating for the batteries or the BBC. The 230V AC bus is distributed throughout the vessel through an conventional MCB fuse box. Therefore, it is not feasible to program dynamic limitations or constraints in the SFC. If the two PVSD’s and the TVSD is limited to available current, the load drawn by the SFC and the HPU can operate free of constraints. Consequently, there must be a defined available overhead power, equal to the largest load peak through the HPU or the SFC. While the HPU is running intermittent, its nominal power must be available in case the compression pump would start. For the SFC, all thermostat controlled heating power should be included in this overhead power reserve. In situations discharging the batteries, DC bus power balance can be described with equation (12 to 14):

$$I_{into\_bus\_max} = I_{BBC\_max} \qquad (12)$$

$$I_{out\_from\_bus} = I_{Propulsion\_VSD1} + I_{Propulsion\_VSD2} + I_{Thrust\_VSD} + I_{230V\_SFC} + I_{HPU} \qquad (13)$$

$$P_{Available} = 600 \cdot (I_{BBC\_max} - (I_{Propulsion\_VSD1} + I_{Propulsion\_VSD2} + I_{Thrust\_VSD} + I_{230V\_SFC} + I_{HPU})) \qquad (14)$$

To prevent that intermittent loads, fail to connect, there should always be available power for them to start. This suggests that the current limits in the variable speed drives for propulsion, and bow thrusting, should be made dynamic. The dynamic limit should assure that the available power always is higher than the sum of intermittent loads.

In situations charging the batteries, the BBC is loading the DC bus. Power balance is maintained by limiting the BBC current to the maximum current available through the CRC. This limit should represent the lowest current rating in the shore connection chain. The SFC carries intermittent loads while charging. Some overhead power reserve will still be necessary. In situations charging the batteries, the DC bus power balance can be described by equation (15 to 17).

$$I_{into\_bus\_max} = I_{CRC\_max} \quad (15)$$

$$I_{out\_from\_bus} = I_{230V\_SFC} + I_{HPU} + I_{BBC} \quad (16)$$

$$P_{Available} = 600 \cdot (I_{CRC\_max} - (I_{230V\_SFC} + I_{HPU} + I_{BBC})) \quad (17)$$

When charging, there will not be any propulsion or bow thruster load present. To prevent intermittent loads from connection failure, there should always be available power for them to start. This suggests that the current limit in the BBC, should be made dynamic while charging as well. The dynamic limit should assure that the available power always is higher than the sum of intermittent loads.

Information about the available power should be visible to the operator. This way, an indirectly control of the available power is possible, by making choices regarding the general loading on the 230 V grid.

4.5.2 HEAT CONTROL

Heat is a base load that will be a constant connected intermittent load during the entire working day. In an aluminium vessel, the heat easily escapes through the hull. Consequently, an intelligent temperature control is needed to ensure that no room is heated to higher temperatures than necessary.

Some rooms in the vessel contains equipment that might be sensitive for temperature changes. The battery room, the bridge and rooms with open electric circuitry is examples of such rooms. To be able to prioritize heat distribution, heated rooms should be divided into priority zones. If the energy level is low. The temperature setting in selected rooms should be automatically reduced to a minimum.

To reduce the energy consumption for heat, the vessel should be preheated before the shore cable is disconnected. This can be achieved by pre-setting a timer. The preheating temperature setpoint should be higher than normal operating temperature. This way it will take longer for the thermostat load will kick in.

4.5.3 LOAD SHEDDING

Normally load shedding refers to actions taken when the power balance on the electrical distribution system is in deficit. When the loading on an AC distribution system is higher than the production, the speed of connected rotating machinery will decrease. The energy preserved in the rotating machinery will decrease and consequently the system frequency will decrease. By disconnecting unprioritized loads, the load shedding algorithm prevents the frequency to decrease below a defined minimum. As the production capacities connected to the distribution is relative low compared to the potential deficit, the load shedding algorithm need to act fast in an AC distribution system.

In this vessel, the distribution system is a DC grid fed from a battery as the energy storage. The power balance issue is handled by limits in the connected converters. Load shedding refers to actions taken when prioritized loads demand more power than maximum available from the batteries through the BBC. The programmed limits in the converters will assure that the system will not operate in deficit power balance. Therefore, load shedding doesn’t need to be controlled by a fast, automatic algorithm. It can be realized by presenting a list of suggested load sheds to the operator.

Equipment crucial to navigation and manoeuvring should never be limited or cut from power supply. Neither should the BMS or systems crucial to temperature control of the batteries as cooling fans or battery room heating.

4.5.4 MONITORING AND MEASUREMENTS

Monitoring refers to the parameters available to the operator through the EMS HMI or other external monitoring equipment. These are parameters that provide the vessel operator with the necessary information to make the best choices for safe manoeuvring and energy efficient operation. The following parameters should be made available for the operator:

- Battery SOC [%]
- Instantaneous total power consumption [W]
- Available overhead power [W]
- Propeller speed [rpm]
- Percent of full propulsion power [%]
- Temperatures in battery and propulsion motor [ºC]
- Temperatures in heated rooms [ºC]

Measurements refers to the parameters available for logging or control. It should be possible for technical personal to select logging amongst all system parameters. Preferably divided into categories. Specially for tuning the Simulink design model, such logging is important. For the model tuning, following parameters should be made available for logging:

- Battery current [A]
- All converter currents [A]
- Instantaneous power consumption in all converters [W]
- Propulsion motors speed and torque [rpm, Nm]
- Vessel speed [knots]

These parameters will serve as input to tune the Simulink model to convergence.

4.5.5 ENERGY ESTIMATES AND LIMITATIONS

Batteries being the only power source, it can be thought of as a small fuel tank. To assure that there will be enough energy in the batteries to complete the journey back to home base, the EMS should record the energy consumption and motor speed on the way out to the site. If the propeller speed is kept the same, changes in weather and sea margin is the main component of the difference between the energy consumption to and from site. Adding a 15 % compensation for weather and sea margin, the recorded energy on the way out can serve as an alarm level for battery SOC. When the available energy on the batteries is less than this alarm level, the operator gets an alarm message. This should trigger a choice between three options:

1. Begin return journey
2. Perform additional charging on site before return journey
3. Perform return journey at reduced speed

Further energy consumption estimates can be added as the vessel performance data is recorded. Following estimates is preferable in a battery vessel:

- Estimated time until batteries are empty, based on current loading
- Estimated time until batteries are empty, based on average loading last (operator choice) hours
- Estimated distance until batteries are empty, based on current vessel speed
- Estimated distance until batteries are empty, based on (operator choice) knots

4.5.6 COMPONENT FAILURE AND ACTION

Battery failure – 11 battery modules make up one battery string. The battery pack consists of five strings. If one of the modules fail, the BMS will disconnect the faulty string. Failure in one string leaves four remaining strings. The capacity estimation might not be correct, and the remaining strings should preferably be fully charged if possible before returning home.

BBC failure – In situations discharging the batteries, the BBC controls the voltage on the DC bus. A failure in the BBC will initiate a bypass, allowing the battery pack to feed directly into the DC bus. This forces the DC bus to the same voltage level as the batteries. All connected converters should immediately change parameter settings for the DC feed voltage. The system might operate as usual, but the BBC is no longer able to limit the load current. A new set of parameters for current limits should be fed to the connected converters.

CRC failure – If the CRC fails, there is no possible way to charge the batteries. Energy estimates for the return journey should be made before leaving, if the CRC fails while the vessel is at sea. Immediate action is to disconnect the CRC from both the DC bridge and the shore connection.

SFC failure – All equipment for navigation and manoeuvring is supplied through the 230 V SFC. Battery management systems is also dependent of the 230 V supply voltage. This equipment should be fed through an UPS system with the sufficient capacity to supply critical equipment for as long as it takes to reach the home port.

Propulsion VSD failure – If one of the propulsion converters fail, it will be disconnected from the DC bridge. It is not possible to drive the permanent magnet machine without a converter. Propulsion is still possible in single propeller propulsion. If two propulsion VSDs fail, it will not be possible to manoeuvre the vessel safely. The vessel should immediately anchor up and call for assistance.

Bow thruster VSD failure – The bow thruster is not critical for manoeuvring. If the bow thruster VSD fails, it will be disconnected from the DC bus. Remaining system will operate as usual.

HPU VSD failure – If the HPU VSD fail it will be disconnected from, the DC bus. If hydraulic actuators are in use, the load should immediately be secured, as the system might lose pressure without an active hydraulic pump system.

5 CONCLUSIONS

5.1 MODEL DESIGN

Dynamic modeling of an all-electric battery vessel driven by an IPMSM propulsion plant is possible. The simulation results will strongly depend on adequate tuning according to data from sea trial of the vessel. If convergence criterion is fulfilled, the model can be used for design purposes. This way, the model can contribute to time efficient estimates of the needed battery capacity in a battery vessel. It can contribute to the design of tailor-made energy storages for battery vessels with specific operation patterns.

5.2 FUNCTIONAL DESCRIPTION

The proposed functional description in this thesis is far from a complete description of the EMS. It is more of a presentation of ideas of control and functionality, discovered through the work designing a dynamic model of the vessel. It is not possible to conclude whether the proposed functionality will work as described before the sea trial. All connected power components have a defined set of alarm parameters that need to be included in the system. This is not described to its full in the proposed functional description.

Still, important aspects have been enlightened. Considerations regarding power limits and energy efficient control is worth including in the design of the EMS. The simulation project has contributed to expand the bases of which an EMS prototype can be designed.

5.3 RECOMMENDATION FOR FURTHER WORK

This thesis has uncovered several areas that should be further explored. The following list may be subject for exploration in future bachelor or master's degree projects:

- In section 4.5.1, power control is proposed handled by a set of dynamic current limits distributed to the limit parameters in the connected converters. It would be interesting to explore different control strategies to control the prioritized consumers when operating near the maximum power of the supply chain.
- The generic model of a lithium battery can be parametrized with very high accuracy. But the producer of the batteries will not share such detailed parameters of the batteries. It would be interesting to explore how laboratory experiments on a battery module can provide the necessary parameters for accurate parametrisation of the generic battery model in MATLAB.
- In section 4.5.5, its suggested that several types of energy estimates could contribute to energy efficient operation of the vessel. It would be interesting to explore different energy estimate algorithms, and how they perform compared to logged data during sea trial.

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APPENDIX 1 – MOTOR DATA

YOUR PERMANENT POWER

TECHNICAL SPECIFICATION:

Permanent Magnet Motor TEMA Motor type: LPMR300 liquid cooled

Electric synchronous motor, with embedded permanent magnets (IPM) on rotor side (PMS, PMAC), variable speed, Inverter driven

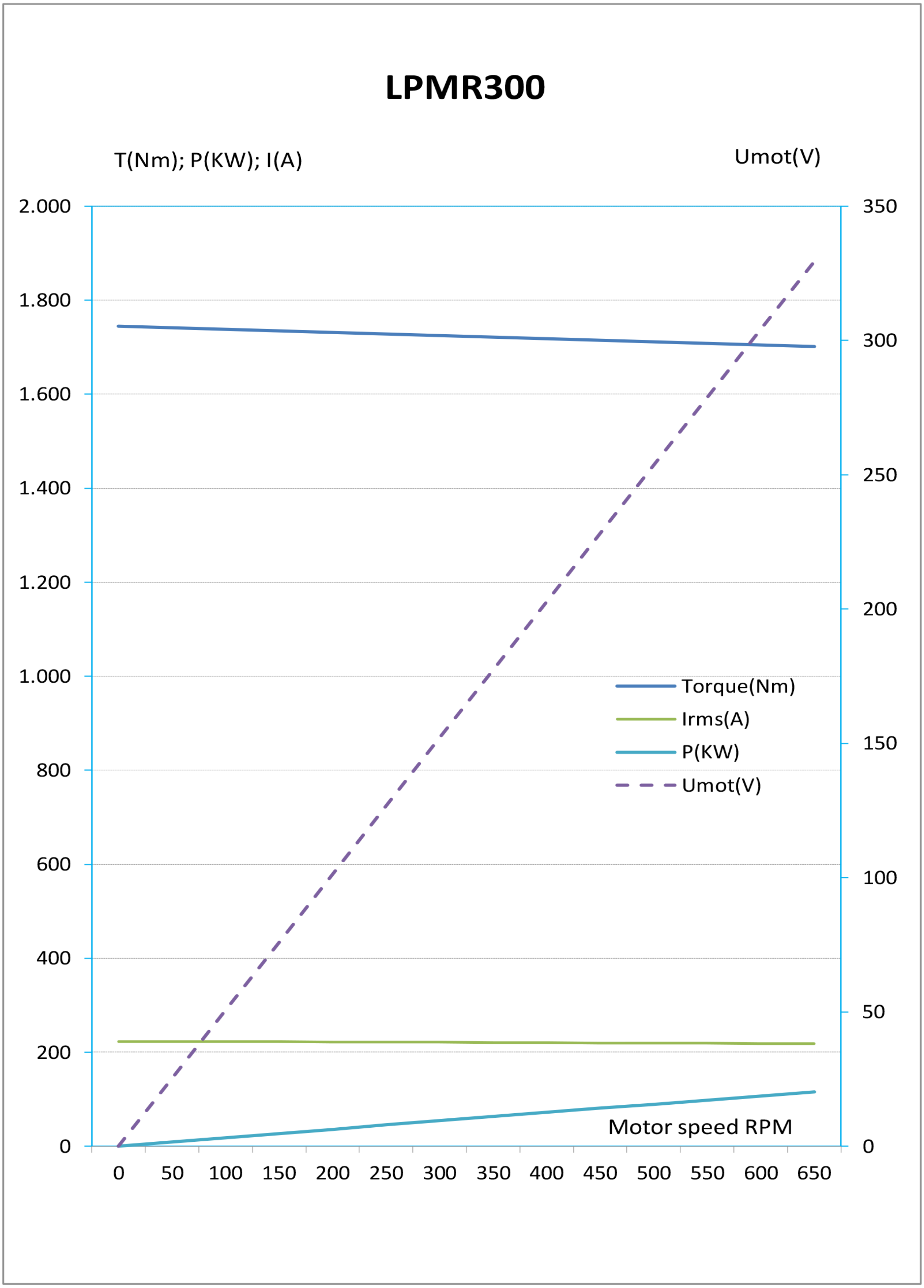
Pnom (S1)	107KW@600rpm
Inv.PwrSupply Un	470-600Vdc
Nominal speed	600RPM
Nominal torque	1704Nm@600rpm
Nominal torque	1745Nm@0rpm
Phase current	218Arms
BEMF	461Vrms/Krpm
No of Poles	6
Nominal f	30Hz@600rpm
Over speed	1100 RPM (no load)
Phase number	3
Phase connection	Y
Power factor	0.77-1.00
Eficiency	96.9%
Isolation Class	F
Magnets type	NdBFe
Ambient temp	25°C
Anti/condensation heater	100W
Overload	110% / 1min (S2)
Demag resistance	3,5 x Inom
Sensors	Pt100 built in Winding temperature sensors
Feedback Sensor:	Resolver TAMAGAWA TS2620N21E11
Bering type	DE (120) 6220-2Z C3, NDE (100) 6220-2Z C3 (Deep groove ball bearings)
Rotation	CC & CCW
Mechanical protection	IP24
Mounting method:	Side mounting brackets
Cooling system:	Liquid cooling with inner air circulation introduced by fan wheel fixed on motor shaft NDE (IC411)
Materials:	End Shields, Housing, Terminal Box, Fan: Steel
Connections:	Screw terminal with power cables glands Connectors for encoder end signal cable terminals for temperature sensors

MOTOR LPMR300

RPM	***Nm***	***A***	***BEMF***	***Umot***
0	1745	222,50	0,0	0,0
1400	1650	210,39	645,1	709,6
1800	1593	203,12	829,4	912,4
2000	1550	197,64	921,6	1.013,8

EMF	9,6	V/z/seg/Krpm		
Z	8	turns		
Seg	6	segments		
Rph-ph		mOHM		
Rph		mOHM		
Ld	3,9936	mH		
Lqns	14,3360	mH	Lq/Ld:	3,59
Lqsat	6,4000	mH	Lq/Ld:	1,60

Pnom	107	KW
Inom	218	Arms
Tnom	1704	Nm
Tpeak	2130	Nm
Effic	96,9	%
BEMF	460,8	Vrms/Krpm
Nnom	600	rpm
Nmax	800	rpm
Novsp	1100	rpm
Isolation	H	class
Temp	F	Class
Ld		mH/I=0A
Lq		mH/I=0A


LPMR300
T(Nm); P(KW); I(A)
Umot(V)
2.000
1.800
1.600
1.400
1.200
1.000
800
600
400
200
0
350
300
250
200
150
100
50
0
Torque(Nm)
Irms(A)
P(KW)
Umot(V)
Motor speed RPM
0
50
100
150
200
250
300
350
400
450
500
550
600
650

RPM	***T(Nm)***	***Imot(A)***	***BEMF(V)***	***Umot(V)***	***P(KW)***	***f(Hz)***	***Udc***
0	1745	223	0	0	0	0,0	0
50	1742	223	23	25	9	2,5	36
100	1738	223	46	51	18	5,0	71
150	1735	222	69	76	27	7,5	107
200	1731	222	92	101	36	10,0	143
250	1728	221	115	127	45	12,5	179
300	1725	221	138	152	54	15,0	214
350	1721	221	161	177	63	17,5	250
400	1718	220	184	203	72	20,0	286
450	1714	220	207	228	81	22,5	322
500	1711	219	230	253	90	25,0	357
550	1708	219	253	279	98	27,5	393
600	1704	218	276	304	107	30,0	429
650	1701	218	300	329	116	32,5	465

APPENDIX 2 – HULL RESISTANCE DATA