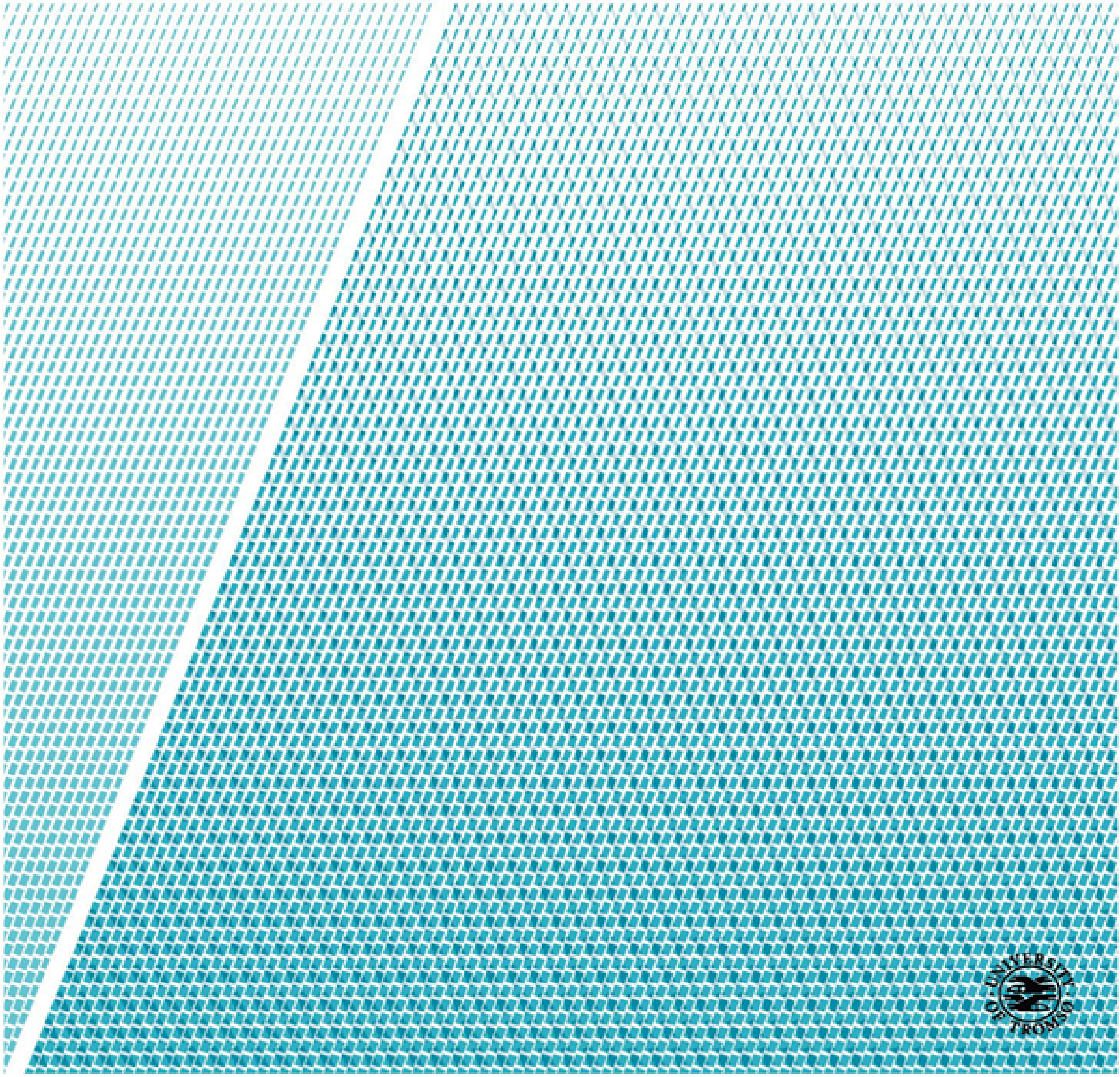
UiT
THE ARCTIC
UNIVERSITY
OF NORWAY

Faculty of Engineering Science and Technology
Department of Electrical Engineering

Application of electric vehicle charging solutions on small maritime vessels

Diploma thesis for Master degree in Technology

Maya Mandasari



Acknowledgements

During my Master's degree program, I have experienced many different things. I have got to know my self better and learned how be self-disciplined and work hard. I have also met a lot of new people and became good friends with some of my fellow students. I have enjoyed studying together and have both serious and fun discussions in the subjects we had. I am very grateful to have come this far and have the privilege to take a Master's degree program.

Firstly, I express my special gratitude to my supervisor, Associate Professor Bjarte Hoff for his kind guidance, support, and favour throughout the thesis period. You have gone above and beyond my expectations.

Second, I would like to thank my lovely mother Ismai Levik and my beautiful sister Dewi Andriani for their love, encouragement, and support during my studies.

Third, I thank my dear friend Hussein Mahdi who has been by my side through this whole Master's program and have taught me so much about electrical engineering. I am amazed by your willingness to help others, and it makes me proud to call you my friend.

Finally, my most heartfelt appreciation goes to my lovely Martin Andresen, for quiting your job and moving to Narvik to take a Masters degree together with me. Your driving skills to the grocery store through winter times have saved me because I got the chance to cook and eat delicious food. Thank you for your love and patience, it has made me strong, and I could not finish this Master's program without you. I am so lucky to have you in my life.

Abstract

This thesis explores various charging standards for electric vehicles with the goal to find a standard that can be implemented in an electric maritime vessel (EMV). Combined charging system 2.0 (CCS2) is selected and the standard is explained in detail along with the necessary power electronics. Several Matlab and dSPACE simulations is made to test the charging and communication. A laboratory experiment is conducted with two programmable logic controllers, an electric vehicle charging controller and two power line carrier communication units. By use of Matlab and e!COCKPIT the equipment is programmed, controlled and monitored. The combination of the theoretical work, the simulations and the experiment works as a base for further work on how CCS2 can be implemented in an EMV.

Table of Contents

Appendices

List of Figures

List of Tables

List of Abbreviations

AC	Alternating Current
BEV	Battery Electric Vehicles
BMS	Battery Management System
CAN	Controller Area Network
CC	Charging Controller
CCR	Charging Current Restriction
CCS	Combined Charging System
CHAdeMO	CHArge de MOve
CP	Control Pilot
DC	Direct Current
EMV	Electrical Maritime Vessel
EV	Electrical Vehicles
EVSE	Electric Vehicle Supply Equipment
GM	General Motor
IC	Internal Combustion
Li-ion	Lithium-Ion
MPPT	Maximum Power Point Tracking
OPC	Open Platform Communications
PLC	Programmable Logic Controller
PLCC	Power Line Carrier Communication
PMS	Power Management System
PMSM	Permanent Magnet Synchronous Motors
PP	Proximity Pilot
PV	Photovoltaic
SoC	State of Charge
VAT	Value Added Tax
VSI	Voltage Source Inverter

1 Introduction

1.1 Background

Battery electric vehicles (BEVs) was invented in the 1890s by Nikola Tesla, George Westinghouse, and Thomas Edison. They established the usage of alternating-current (AC) and direct-current (DC) power systems. At that time, the BEVs utilized lead-acid batteries and a DC power system to be able to start. Nevertheless, the low sales price of gasoline in the 1900s made the internal-combustion (IC) vehicles more attractive compared to the BEVs and made it difficult for the BEVs technology to compete [1].

Late in the 1980s General Motor (GM) produced and designed electric vehicles (EV) known as the GM EV1. Like the cars invented almost a decade earlier, the GM EV1 utilized a lead-acid battery, but now it also had a lightweight construction and low drag design. GM wanted to reduce air pollution like smoke and fog, which has spread in American cities because of the IC engine vehicles. Nevertheless, the lack of support from the government and less consumer demand for green technologies made it hard to keep the business going [1].

Nowadays, electric vehicles are constructed with a very high number of lithium-ion (Li-ion) cells. Li-ion cells have a high energy density, which makes it more space efficient because it provides longer EV range and has the capability to be rapidly charged and discharged. Many large car companies have invested in the development of innovative electric motors and batteries. At the same time, the government in several countries has provided many incentives for the EV owners. In Norway, for example, the government has for many years provided them with free toll roads, ferries, and parking as well as no import tax or VAT (value added tax) on new cars [2]. Because of the geographically large area and distance in Norway, the government also put more focus in infrastructure planning and building a strong network of fast EV charging stations for CHAdeMO charging, CCS (Combined Charging System) charging and Tesla Supercharger stations. The incentives and the reliability of charging made people in Norway more interested in buying electric vehicles [3].

The global environmental problems still face the world today, and it has been a major focus to work on reducing climate emissions and air pollution, both on-shore and off-shore. In 2014 a fully electric car ferry, MF Ampere, was built by Fjellstrand AS in Norway [4]. In northern Norway, a local company named Grovfjord Mek. Verksted AS has taken the initiative to develop a battery electric maritime fish farming vessels [5].

They have succeeded in building the world first electric fish farming vessel and the vessels supposed to be used as a work boat for the aquaculture industry. GMV Zero, as shown in Figure 1 is a 100% battery electric driven vessel with zero emission, which is environmentally friendly. In order to reduce climate emissions and air pollution, they plan to build more of this type of vessels [6].

Figure 1: GMV Zero battery propulsion maritime vessel [7]

Table 1: Specifications of GMV Zero [5]

Specifications	
Parameter	**Value**
Length	13.97 m
Width	7.6 m
Depth	2.40 m
Battery capacity	350 kWh
Charging power	2×87 kW
Charging solution	2×125 A plug 400 V
Motor output	2×107 kW, 600 rpm
Max speed	10 knots
Nominal speed	8 knots
Navigation distance	26 nautical miles at nominal speed

The specifications of GMV Zero is shown above in Table 1 with the battery capacity of 350 kWh and charging power 2×87 kW. The charging hour has not been mentioned and also the maximum navigation service. Referring from the specifications of the relation between the speed and distance of the navigation's service when the vessel is operated at the nominal speed and has reached a distance of 26 nmi approximately within 3 hours which has been calculated by using the Formula 1.

$$t_{(h)} = \frac{d_{(nmi)}}{v_{(kn)}} \tag{1}$$

1.2 Project Description

Application of electric vehicle charging solutions on small electric maritime vessels. After conducting a literature review on charging standards and communication protocols for electric vehicle charging, one should be selected for implementation in GMV Zero. Next is to design and simulate a charging control algorithm in MATLAB and Simulink programming. Subsequently, build a setup for the communication between dSPACE Control-desk layout and Power Line Carrier Communication (PLCC) through a Programmable Logic Control (PLC) to the Electric Vehicle Charging Controller (EVCC) board.

1.3 Problem Analysis

The GMV Zero is 100 percent battery electric driven maritime vessel, and it needs to be charged. The charging solution for the GMV Zero that has been used until today is by connecting the industrial plug on the vessel, as shown in Figure 2a with a 400 V shore connection plug. The problem is that the users are not informed about if the charging has started or what the battery charge level is during charging. This makes the ship very vulnerable if one or more components are not working as they supposed to. It is a risky situation that can incur large costs for the owner of the vessel. Therefore it needs to be designed, programmed and simulated a communication protocol and control algorithm for the vessel to be safer and more profitable.

By searching on the literature of the charging standard that exists and has been used for electric vehicles today, convert it so it possible to implement on the EMVs is the goal of this project. While also finding a solution for communication between the charging station and the vessel, the possibility of full monitoring during the charging operation of the vessels. Such a type of control unit that can be connected with a PLCC that will provide useful information for the user and serve the interface to the user and possible show the critical information through a screen display to avoid the unbalanced voltage and current flow from the grid to the vessel.

(a) 400V 3-phase industrial plug

(b) Low voltage shore connection plug

Figure 2: Charging plugs

1.4 Main Objectives

The main objectives of the project are to create a model and able to simulate the charging solution that initially has been developed for electric vehicles and evaluate it, so it will be applicable to use on small EMVs.

The main objectives of the thesis is listed down below :

- Literature search of charging standard and communication protocols for electric vehicles.
- Evaluate the use of EV standards on EMVs.
- Simulate one or more charging solution with focus on power electronics and communication protocols.
- Design and propose a small-scale laboratory test setup for selected solutions.
- Emulation of charging control algorithms using hardware in the loop.

1.5 Project Limitations

In this project, the focus will be on the CCS 2.0 charging standard communication protocol and control algorithms. Other charging standards like CHAdeMO, Tesla and GB/T will not be considered.

During the project, small scale laboratory experiments with an approach similar to CCS charging standard will be conducted. However, a full scale and exact CCS charging standard experiment is not possible as it would take too much time and resources. MATLAB and Simulink, dSPACE and e!COCKPIT will be used for the experiments.

2 Literature review

2.1 Electric Vehicles

Electric vehicles (EV) is using electric energy from an on-board battery storage system and electric motor as powertrain applications. The on-board battery is the primary power source and has the main task to supply the power to all components in the vehicle. The EV gives zero tailpipe emissions when operated. Moreover, the EV powertrain and the fuel consumption is more efficient that will give more economic benefits compared to the IC engine powertrain [1].

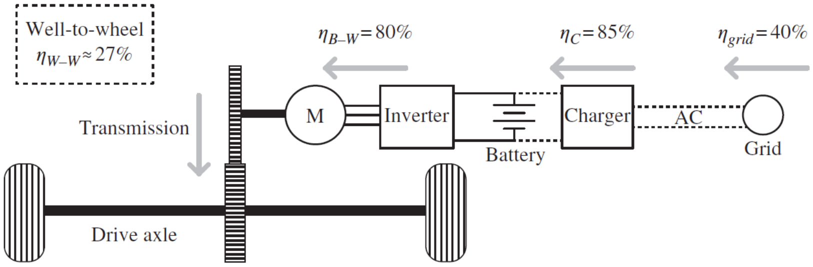


Figure 3: EV energy flow and powertrain architecture [1]

The EV need to be recharged from the grid power source and the basic powertrain for the EV is shown in Figure 3. It can be charged with AC power for slow charging and DC power for fast charging. The EV powertrain system is constructed with the following components.

- **Electric Motors** AC or DC motor. The electrical energy which been supplied from the battery to electric motor and the motor characteristic to transform the electrical energy to the mechanical energy [8].
- **Electric Generators** The generator task is to transform mechanical energy to electrical energy.
- **Inverters** Also known as static inverters, is an power electronic device that changes the DC source from the battery to AC output voltages in able to powering the AC motor. The battery storage system have a direct connection with the motor.
- **Chargers** The electricity flow through the charger and it consist of a rectifier to able to transform the AC power to DC power and charging the battery storage system. The charger also often build with the charge controller to optimize the charging process, which will affect the battery lifetime.
- **Battery storage system** consist of battery packs that are required to be recharged. The dominant type of battery that has been used in EV today is made with a large number of lithium-ion (Li-ion) cells also called for a secondary battery. It has a DC output voltage and has characteristic to be charged and discharged.

2.2 Electric Maritime Vessels

Global environmental problems have been in focus for a long time. The increased number of gasoline and diesel IC engines in use gives a negative effect on human and other living organisms. Among it will impair physical and mental health, damage the natural ecological balance of sea and urban. As it is related to maritime transport, port, air, water, and noise pollution are just a few problems that exist today [9].

Maritime transport is the worlds largest and most important transportation industry [10], and less expensive compared to transportation by air. Huge container ships are responsible for around 90 percent of the global transportation of goods [11]. Passenger and car ferries used for public transportation, small fish farming vessel and regular people who own the boat for their private transportation. Unfortunately, many of those maritime transportation's are still implemented with an IC engine, where the use of gasoline and diesel fuel will continue which means the greenhouse emissions, air and oil pollution in seawater will also continue to increase [11]. Therefore it has gained the initiative among people and evokes big companies to invest in developing the battery electric propulsion ship in order to protect the environment and great future development of the new trend technology [12].

Battery electric propulsion ships are also called electric maritime vessels (EMVs). They use the same principle as an electric vehicle that has on-board storage batteries as the main power source and electric drives for propulsion. The electric drive typical features an inverter, electric motor, and controls [1].

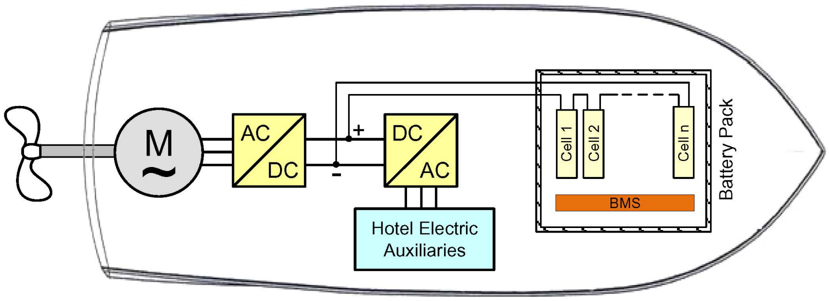


Figure 4: Electric propulsion system block diagram [13]

A simple block diagram of electric propulsion system with DC architecture in the vessel can be seen in Figure 4. The systems are placed in the vessel hull it consists of an electric motor, power electronics converters AC-DC and DC-DC, hotel electric auxiliaries, and battery pack. The charger connection usually has a directly connected with the batteries pack.

Since the vessels are powering with the storage batteries, means the vessels didn't use any fuel same as internal-combustion ships and there is no oily stink in the ships [14]. Another benefit is low-vibration and low-noise, for public transportation it will give a more pleasant experience for the travel and fresh air working environment for the worker.

The capacity of the battery on-board depends on what application the boat is going to be used for. According to the size of the vessels itself, operating distance, the speed, and total carry weight have a big impact on the consumption of electric power [14]. However, bigger battery capacity requires a bigger area of the vessel hull and the more expensive it is. The weight of the batteries pack is heavier compared to fuel. Since the capacity of the batteries and weight is proportional to each other, means the bigger it is the heavier it will be on-board. It must be balanced to be able to operate sufficiently [15].

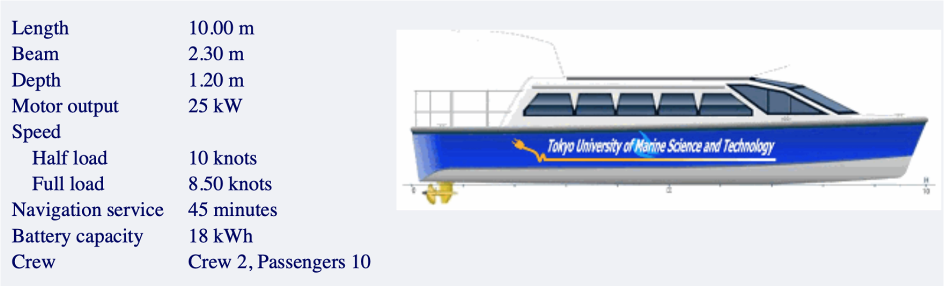
The price of the batteries is decreasing each year, although it is still expensive compared to the fuel price. But after a while it will be money savings, because the price of the electricity needed to recharge the battery is cheaper than the fuel price. To make efficient, it is a requirement to build a short time DC charger in the harbour. The availability of short time DC charger will help to minimise the size of installed battery capacity in the vessel, which also means reducing the weight of the vessel.

Another impact that can affect the performance range of the electric maritime vessels is when there is changing on environmental conditions where the weather is rough. Big waves, high tidal current, and high wind speed increase the resistance against the vessels which will lead to higher power consumption than when the water remains quiet. Therefore leeway is necessary when choosing the batteries capacity in case of unexpected weather changes [14]. The rough weather that has been mentioned above will affect the energy losses of the battery and it can be a big challenge to manage.

2.3 Existing Solutions of Electric Maritime Vessels

Examples of few battery electric maritime vessels that exist today is RAICHO-I, all electric catamaran, and Eco friendly Electric propulsion Boat [16], [15] [17]. However, since it is quite a modern type of transportation, the use of battery electric propulsion ships is expected to rise in the future [14]. Another study in [18] of the vessels has also been found out that the energy saving is very high and better than the electric vehicle on the road. An estimation of 13 times in saving performance can be achieved. It is expected that by the installation of renewable energy source in the vessel, further saving can be achieved. The new research areas of electric vessels are the control, the motor, and battery energy storage. It is expected that electric vessel will be replacing a large number of short-range vessels in the next ten years.

RAICHO-I is a type of electric boat that has been produced by Tokyo University of Marine Science and Technology in Japan. It utilises lithium-ion battery cells as the main power source on board and has a quick charging system when docking at harbour [16]. The specifications and a picture of the boat can be seen in Figure 5. ”RAICHO-I” is the first electric boat that use the CHAdeMo charging standard protocol. A quick charging plug-in system that charges up to 80 percent within only 30 minutes. With 80 percent charge it can operate for 35 minutes in full speed, while a fully charged battery gives it 45 minutes of operation.



Length	10.00 m
Beam	2.30 m
Depth	1.20 m
Motor output	25 kW
Speed	
Half load	10 knots
Full load	8.50 knots
Navigation service	45 minutes
Battery capacity	18 kWh
Crew	Crew 2, Passengers 10

Figure 5: Specifications of electric boat ”RAICHO-I” [19]

It is a short running time boat that is best suited as a sightseeing boat or fisheries patrol. The battery capacity of the boat is 18kWh as shown in Figure 5 with total battery weight about 400 kg. To be able to observe the information status of the battery, motor, and error they used a controller area network (CAN) bus as a communication network of a control unit. It is a part of the CHAdeMo charging standard protocol.

The speed of the boat is controlled by a use of a throttle lever and it can be navigated in both calm waters and in open sea. The navigation that they tested is between two campuses with a distance of 7 km. To improve the manoeuvrability of the boat they installed an azimuth thruster and a bow thruster in the boat. The boat features two DC 395V lines for the control system. The first DC line is connected with the battery for energy supply and the other one is used for the main azimuth thruster. The main controller, bow thruster, etc is connected independently by using a DC 24V line that is supplied energy from the solar panel they have installed on the roof.

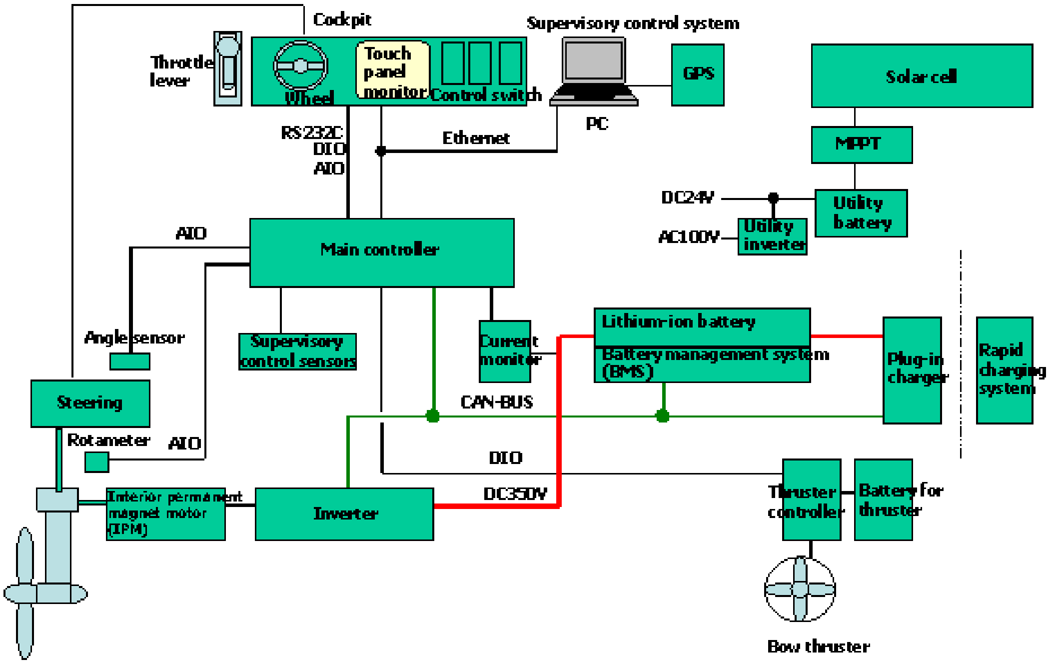
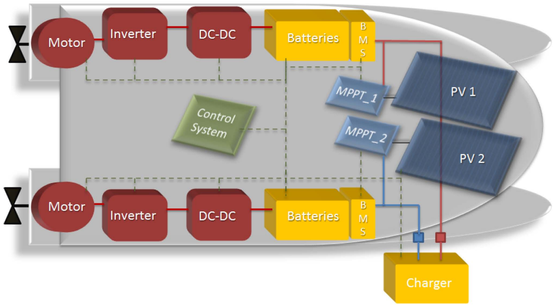


Figure 6: Control system of electric boat ”RAICHO-I” [19]

All Electric Catamaran is a small passenger vessel with zero emissions that can be used for public transportation and water sports events [15]. The purpose is to reduce the water pollution in the lakes and lagoons, mainly in tourists area. The boat is equipped with lithium-ion batteries that can be charged with 14 m^2 photo-voltaic panels that are installed on the roof while it operates. It can also be charged with either a quick charging system (1 hour), or slow charging system (8 hours) that is connected to grid in the harbour. The catamaran is constructed with a drive system of propulsion power up to 100 kW using 96V low voltage battery banks. It consists of two waterproof battery banks with total of 60 batteries cells and weighted 380 kg.

The all Electric Catamaran can reach speeds close to 10 knots, making ideal for use in competitions such as Iron man triathlon and Olympic Games.



(a) Electric system

Parameter	Value
Battery voltage – E	96 V
Battery cells – $LiFePO_4$	3.2 V, 160 Ah
Dc-bus voltage	160 V
Motor – PMSM	2 x 12 kW @ 20 N·m, 5500 rpm
Passenger capacity	12

(b) Specifications

Figure 7: Electric diagram and specifications of the all electric catamaran [15]

A study has been done according to the all electric catamaran that is shown in Figure 7. The study is about how to increase efficiency of the drive system and improve the performance for the Permanent Magnet Synchronous Motors (PMSM) that is used for electric boat.

A dc-dc bidirectional converter that uses highly-coupled inductors to maintain a steady dc-bus which feeding three-state switching cells based voltage source inverter (VSI) that connected with motor drive system. It based of two 12 kW (PMSM). The benefits of using PMSM is easy to assembly and give a high-performance drive due to high efficiency, robust rotor structure, and high power density. The bidirectional improve the breaking performance for the propeller, when its have the ability of regenerating breaking. They want to reduce the voltage harmonic, where it follows to reducing current ripple, mechanical stress, copper and iron losses. To be able to reduce all above they using a three-level VSI and boost converter, and both presents five level waveform. It also give the system higher switching frequency, less switching losses and tolerate heat distribution better.

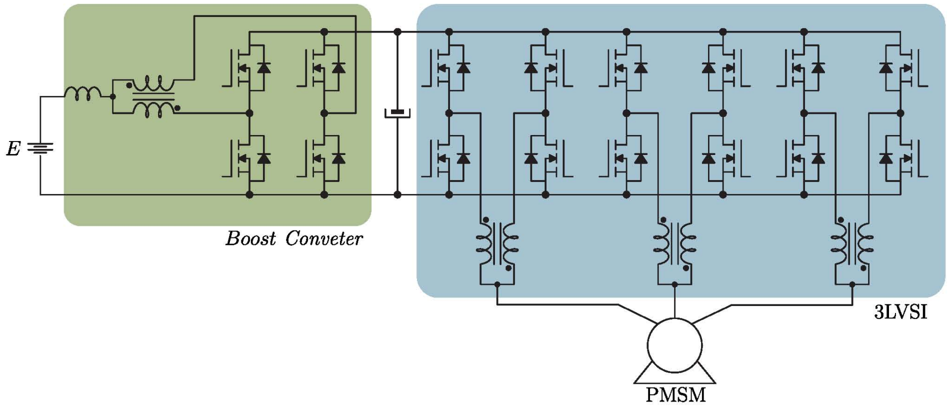


Figure 8: Power converters and the drive system for the all electric catamaran [15]

Communication for the batteries is using the battery management system (BMS) and for the motor is power converters used. PV arrays has independently line through a dc-dc converters for energy supplied to the batteries, it features with maximum power point tracking (MPPT) systems. All components that are mentioned above, are communicating with a central control unit using CAN bus. Through a touch screen display the user can easily observe the status of the boat.

Eco friendly Electric propulsion Boat is a part of a project that has been designed for the Lake Trasimeno, where people who lived on the island Maggiore can utilise the boat as the public transport and protect the environment at the same time [17].

The ferry boat features with lithium-ion batteries that can be charged at any harbour in the surrounding area. In addition to the energy distributed to the grid charging system is coming from renewable sources such as photo-voltaic power plant. With a battery capacity of 226kWh and total weight 2456 kg. The boat is able to operate 11hours without recharging the batteries. The regular travel time is about 1hour, with an operating speed of 6 knots and can fit the passenger capacity of 44-50. The boat is designed as a catamaran because it has low resistance to motion and a minimum draft.

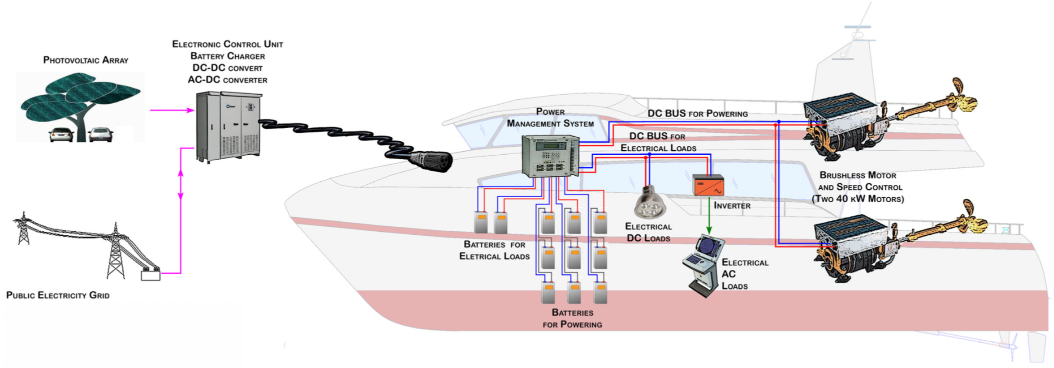


Figure 9: Diagram of Eco friendly Electric Propulsion Boat [17]

Power Management System (PMS) is an innovative solution used to provides the real power and actual transfer energy range from the batteries. By optimal managing and measuring the charge and discharge behaviour of the batteries. It gives the possibility to observe the voltage and the current necessary during the charging and operations of the boat. So it will maintain more safety to the system if a failure occurs of one or more appliances.

2.4 Battery Storage System

Battery storage systems (BSS) is mainly consist of the lithium-ion (Li-ion) cells battery. Li-ion cells are commonly used in today electric propulsion systems and the development of it is yet expected to improve. The capability to store the electric energy, with an important task to provide energy to all the electric appliances in the vessels [18]. By connecting the electric maritime vessel to the electric grid at the harbour so the electricity will flow and fill up energy in the batteries. It can be charged to full at night and used short time DC charging during the day [14]. But before do the charging, certain requirements must be studied and planned when selecting the charging system. it is important to consider the safety, user-friendly, reliability, charging times and power levels, communications, and standardisation [1]. Its important that battery cells is in balanced, to prevent the over voltage and under voltage problem [18]. The battery pack needs to have a battery management system (BMS), by connecting it in series, it able to monitor and control the operative conditions of every single battery cells [13].

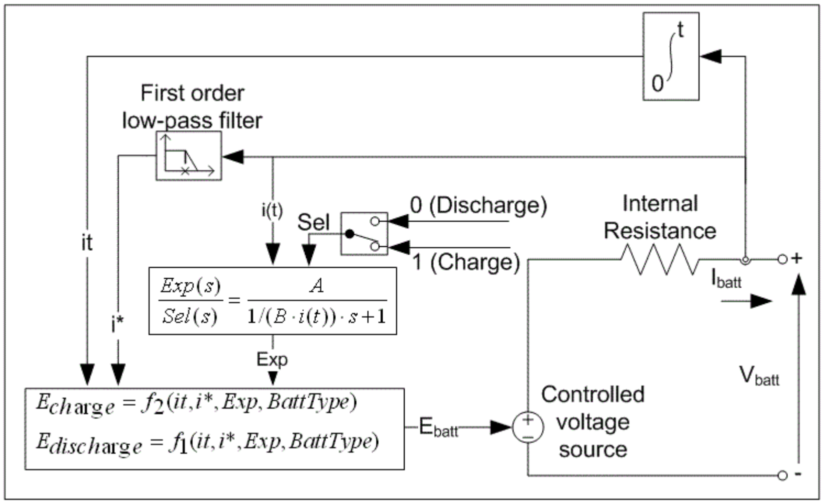


Figure 10: The block model of the battery equivalent circuit

There are two battery terms that are important:

- The state of charge (SOC) is the total battery level that is still on the battery pack. Usually the battery storage system have a connecting line to a DC bi-directional converter and the voltage of the DC bus is determined by SOC [20].
- The depth of discharge (DOD) is the amount of energy that has been discharged from the battery pack.

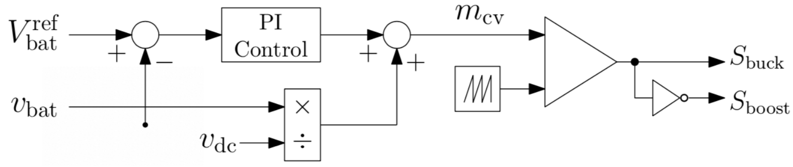
Above terms is often expressed as a percentage. For example if the battery capacity is 50 kWh and 20 kWh has been discharged, the DOD is $\frac{20}{50} \times 100\% = 40\%$. The remaining energy in the pack is 30 kWh, and the SOC is $\frac{30}{50} \times 100\% = 60\%$ [1].

2.5 Regenerative Braking

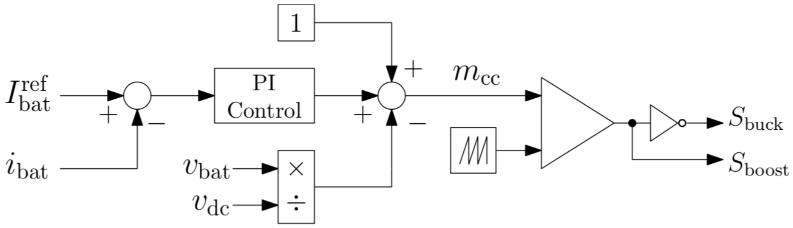
In an EVs, since it featured with the electric drive system which made it possible to regenerate the energy and able to store back the energy to the storage system. The regenerative braking occurs when the road is downward and the car getting a negative downgrade force. It is an advantage that an Evs has compared to a vehicle with IC engines [1]. For the electric maritime vessel, there is no regenerative braking, but instead, known as the plugging mode. By reducing the speed with the expense of high power needed.The plugging mode occurs when the vessel is decelerating and it will produce dynamic energy and recovering that energy to the battery storage system. The water stream below the vessel will produce the dynamic energy and the excess of that energy will supply the regenerative power to the battery storage system [18].

2.6 Constant Current and Constant Voltage Charging Mode

Constant current and constant voltage charging strategy are two methods that can be implement as a battery charger controller. To have better understanding in charging and discharging process.



(a) Constant voltage strategy



(b) Constant current strategy

Figure 11: Charger control for EV battery [21]

In constant voltage (CV) strategy, the current of the charger will continue to flow until the power supply reaches the voltage requirement. When the voltage has reached the set value, the current will then decreased to a minimum value. In constant current (CC) strategy, is a simple form of charging batteries, with approximately 10% of the maximum battery power rate. The battery may be overheating because of the long charging time. Combination of Constant Voltage and Constant Current strategy will allow the fast charging and give less risk for the overheating and overcharging, therefore it is suitable for Lithium-ion cell.

In Constant Voltage (CV) strategy, the battery will be operating as a voltage source. The converter will operate in buck mode and sets from the output duty ratio m_{cv}. When CV mode applies the charging process starting. The voltage gradually increases with the initial SoC, and it will be higher than the starting value. Constant voltage source will generate a suitable output voltage at the desired level. As the batteries are using a practical voltage source, means that the internal resistance (R) produces the same effect as a resistance connected in series with an ideal voltage source. These two series are carry the same current [22].

In contrast with Constant Current (CC) strategy, the battery will operate as a current source, and the output duty ratio sets m_{cc} of the circuit to perform in boost mode converter. When the converter is being controlled by constant current strategy, the EV battery will discharge. By corresponding with the current reference and regulate the output current [21].

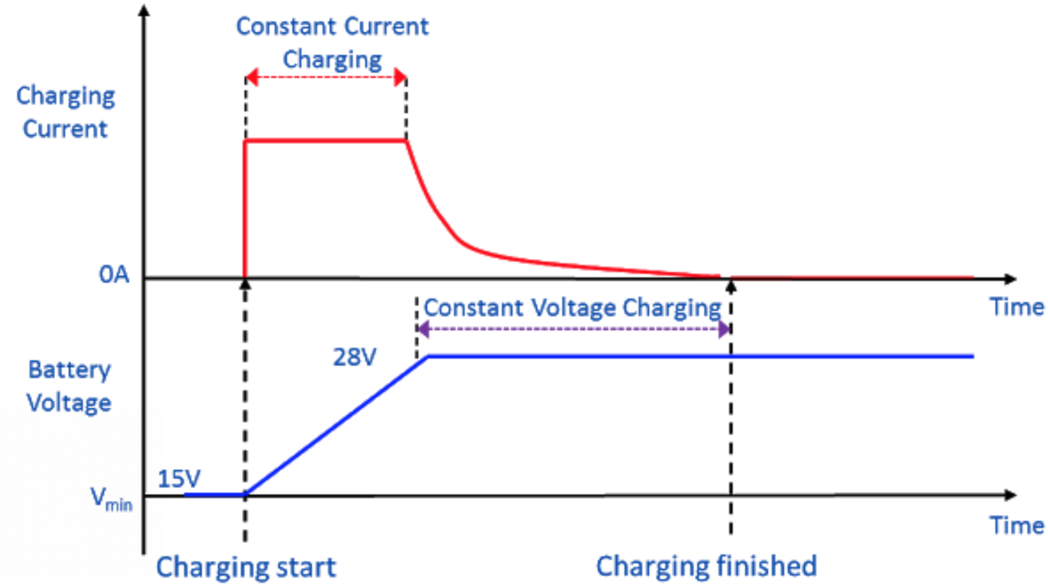


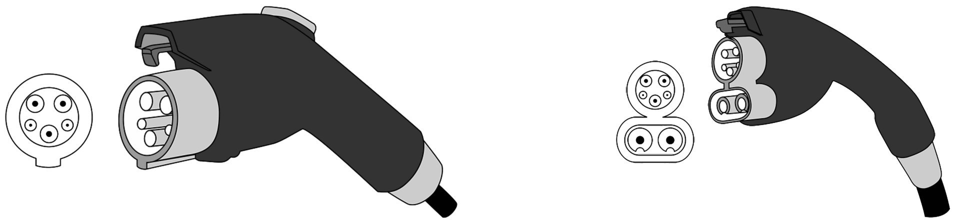
Figure 12: Constant Current and Constant Voltage characteristic [23]

2.7 Technology of Charging System

There are varieties of charging technology that is available for electric vehicles. Every EV brands have their requirements, which follow with the chosen technological approaches, standards, and different type of charging levels or modes. By choosing one of those available EV charging systems and implement it for EMV is still a new trend of technology. The charging system is linked to how the BSS in the EV is being recharged, and there are two main ways to recharge the EV from the power grid: conductive charging and inductive charging [24]. The inductive charging will not be discussed in this thesis.

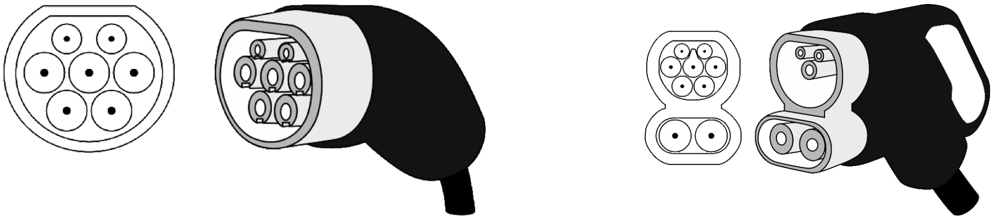
2.7.1 The Conductive Charging System

The conductive charging is the method, where the EV is connected directly with charging infrastructure or the energy supply equipment by using an electrical cable for power delivering [25]. On Figure 13, it is showing different types of EV inlet and plugs that exist today.



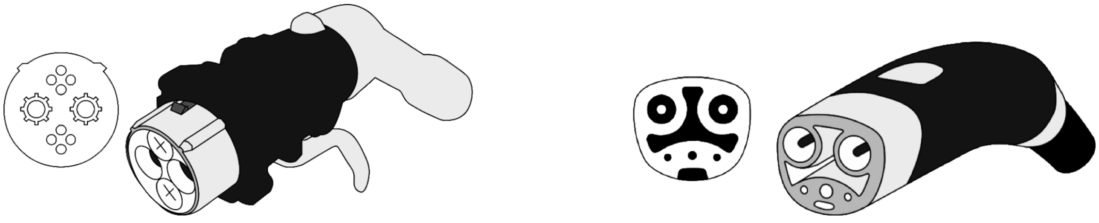
(a) SAE J1772 Type 1

(b) CCS 1.0



(c) Mennekes Type 2

(d) CCS 2.0



(e) CHAdeMO

(f) Tesla

Figure 13: EV charging inlets and plugs [26]

The charging technology that will be studying in this project is the conductive charging system. The EV industry and the EV manufacturers have invented many types of conductive charging, following with their standard. The Norwegian EV association has registered 29 various EVs that people can buy today. Comparison within the range, the price, and warranty. Some of those EVs used the same charging plug, and others use different charging plugs [27].

The conductive charging generally classified into on-board and off-board chargers. The on-board charging means the charger is located inside the vehicle, which the EV owner can slow charging their EV at home or any suitable place. The disadvantage with on-board chargers is the limited power due to the space need, costs, and weight. Compared to the off-board chargers, it has higher power rates and more accessible, since the government is supporting on built and develop more charging station infrastructure along the Norwegian road.

Charging architecture is an essential requirement in the charging technology, the interaction between the EV or EMV and the grid that is consists of electrical power conversions [28].

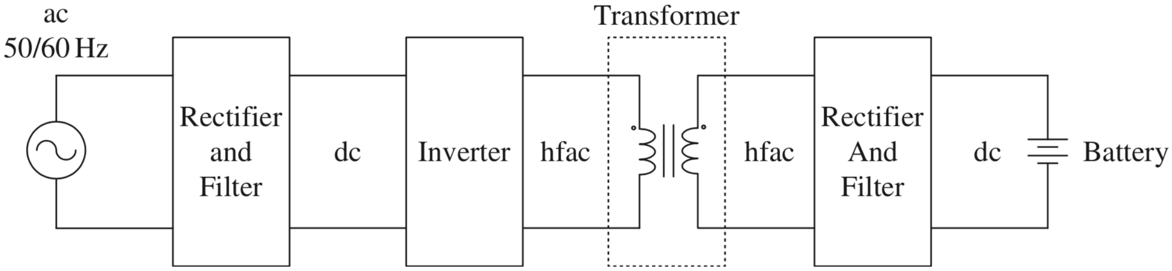
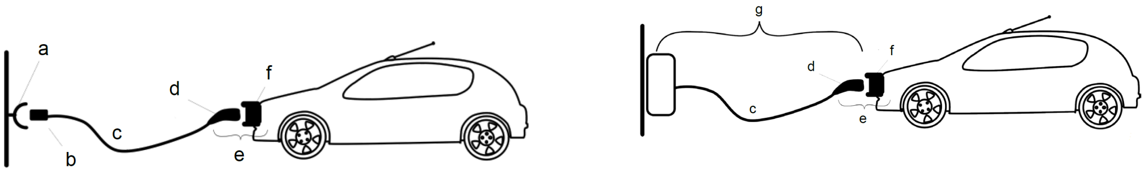


Figure 14: General charging architecture [1]



(a) The AC charging with cable assembly is part of the vehicle

(b) The DC charging with cable assembly is part of the charging station

Figure 15: Different method for connection of an EV to the power grid for charging proposed [29]

Table 2: Letter descriptions [5]

Letter descriptions	
(a) Socket outlet	(e) Vehicle coupler
(b) Plug	(f) Vehicle inlet
(c) Cable	(g) Charging station
(d) Vehicle connector	

2.8 AC Charging Architectures

For AC charging architecture, the cable assembly is part of the vehicle, also meaning as the on-board charge. The alternating current (AC) currents and voltages with electrical frequency at 50 or 60 Hertz are transferred through the electric vehicle supply (EVSE) socket outlet from the electrical grid to the female inlet in the maritime vessel [1].

The battery in the storage system requires direct current (DC) electricity, therefore the AC current need to passed several conversions process before it reaches to the battery. The first stage, are a rectifier and a filter that convert AC to DC waveform. The second stage, an inverter that converts DC to higher frequency AC waveform. The third stage is a transformer which provides more electrical safety in the electrical path between the grid and the battery. The last stage is rectifier and filter from high-frequency AC to DC and supply to the battery in the vessel.

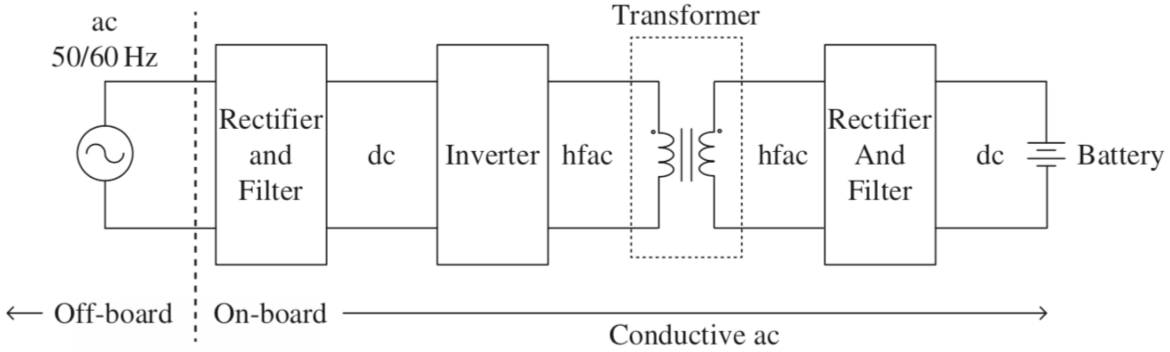


Figure 16: Conductive AC charging architecture [1]

2.9 DC Charging Architectures

The general architecture of DC fast charging station have the cable assembly as the off-board charge modules, which consists of by a step-down DC-DC converter that connected to the power grid through an AC-DC converter and a medium voltage transformer. The DC-DC conversion stage connects the DC-link of the inverter to the battery. The battery voltage is depending on the state of charge (SOC), therefore a battery voltage regulation is required.

The dc fast charge must able to communicate with other appliances, such as pack voltage, charge rate, when to back off. Additionally, for the system to support smart grid things such as borrowing electricity out of the pack, it needs to be able to read the state of charge, as well as request extraction of power. The process of the power flow from the power grid directly to EVs battery can reach up to power levels of 240 kW and known as Level 3 [30].

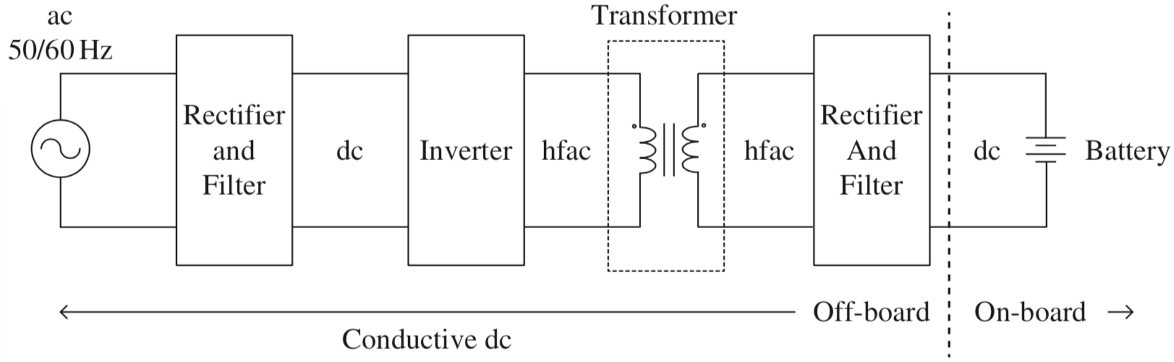


Figure 17: Conductive DC charging architecture [1]

Currently, there are three types of DC charging systems: CCS, CHAdeMO, and Tesla dual charger for AC and DC. This project will only be considered CCS or CCS 2.0 to be precise as they are available for Norwegian users.

2.10 EVs Charging Standards

The increased of EVs users and EV supply equipment plays a critical role in grid integration and daily use. Therefore, several organisations have invented charging standards. There are two type EVs standards that is in used today, one for American and one for European standards. Each standards are divided into different type of power ratings, the configuration for AC and DC voltage [31].

American Standards

Several organisations have established and developed the regulation and standards for the conductive charging systems used in America. Among them is the Society of Automotive Engineers (SAE), the Institute of Electrical and Electronics Engineers (IEEE) and the International Electrotechnical Commission (IEC) [25]. SAE J1772 defines EV charging system architecture that covers the general physical, communication protocol, electrical circuitry, and performance requirements for the EV charging systems. As is shown in Table 3, the EV charging system are classified into AC Level 1, AC Level 2 and DC Level 3.

Table 3: SAE J1772 standards charging level and ratings [25] [31]

Charging Level	Voltage	Max Current/Power	Typical use
AC Level 1 On-board, 1 phase	120 V	16 A/1.9 kW	Slow charging for home/office
AC Level 2 On-board, 1/3 phase	240 V	80 A/19.2 kW	Primary charging for private/ public
DC Level 3 Off-board, 3 phase	200-600 V	400 A/240 kW	Fast charging for public use

AC Level 1 and 2 have a lower power rating than DC Level 3 charging. The DC charging is usually used for public and known as fast DC charging station. The infrastructure for DC charging stations is more complex compared to AC slow charging, because it can delivered much higher power, which means more regulation needed. It is essential to consider safety and reliability due to charging to ease the customers.

Level 1 charging system is the slowest because it using 120 V and have the max current 16 A. No additional infrastructure is required for this level.

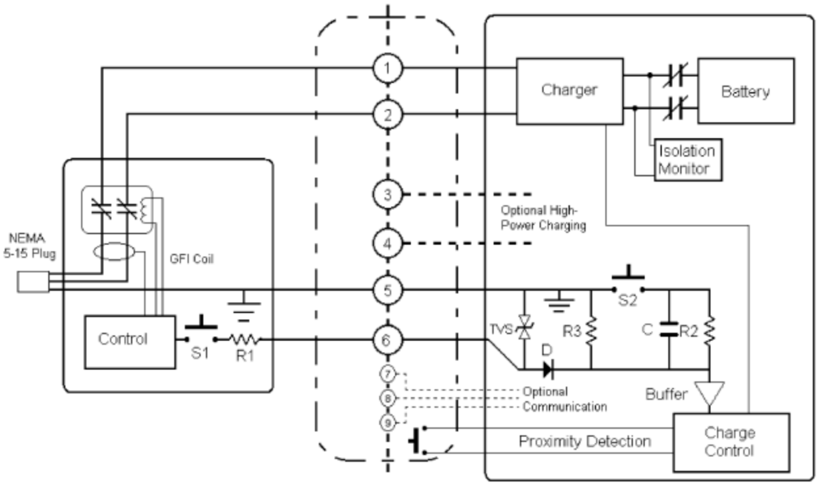


Figure 18: Charging system configuration of AC Level 1

Level 2 charging system is the primary one, has been used for public facilities and private. This level required charging equipment infrastructure and shall be fitted with an on-board charger. It can be charged with single or three phase AC voltage.

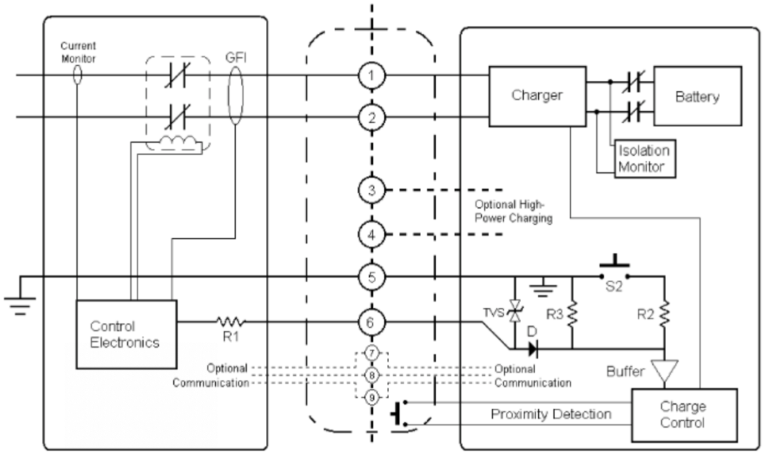
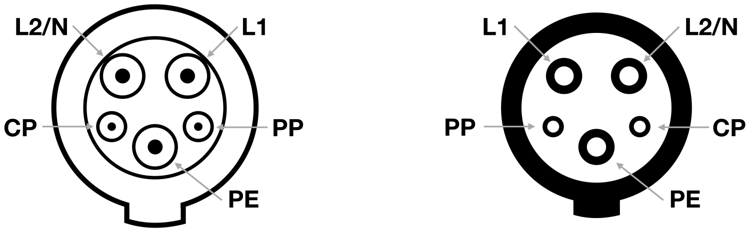


Figure 19: Charging system configuration of AC Level 2

Level 3 charging system is the fastest compared two levels, as mentioned above. This level operates with a three-phase 480 V or may even higher and delivered much higher power. This also requires a complex charging infrastructure equipment.

2.10.1 SAE J1772 Type 1

Type 1 connector is also known as the Yazaki connector after the manufacturer and the plug used in the US and Japan. As presented in Figure 20, the number of power is limited to single phase because they do not have a three-phase power grid and since only single-phase, the maximum power output is lower than Type 2 plug on every Level [24]. The connector consists of 5 pins: earth pin, 2 control pins corresponding with IEC 61851-1, phase (L1, L2/N). The control pins are Control Pilot (CP) and Proximity Pilot (PP) signals, for control the PWM signal is sent over CP pin.



(a) Type 1 vehicle inlet

(b) Type 1 plug

Figure 20: Type 1 vehicle inlet and the charging plug

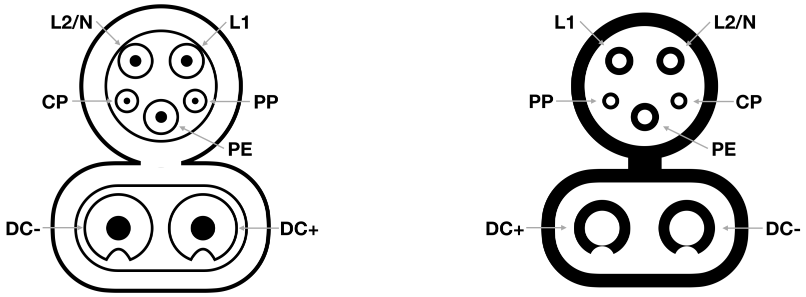
Table 4: SAE J1772 Level 1 and 2

Parameter	**Value**
Connector:	SAE J1772
Voltage:	120 - 240 V
Current:	16 - 80 A
Power:	1.9 -19.2 kW
Charge Level:	1 and 2

2.10.2 Combined Charging System (CCS)/Combo 1.0

The Combined Charging system (CCS) is a charging plug for EV with brands BMW, Audi, and Volkswagen. Society of Automotive Engineers (SAE) has developed the CCS charging standards in CCS 1.0 [32].

The combination of SAE J1772 standard (type 1) plus DC voltage. This charging system is known as CCS 1.0 for use in the US and Japan. It can be use for DC charging. The connector consists of 7 pins: protective earth pin, 2 control pins, AC pins (L1, L2/N) and 2 DC power pins DC+, DC-. The control pins are Control Pilot (CP) and Proximity Pilot (PP) signals, to control the communications with the power grid as PLCC signals on CP pin, plus PE. The communication standards for CCS 1.0, followed according to ISO/IEC 15118-2,3 and DIN SPEC 70121.



(a) CCS 1.0 vehicle inlet (b) CCS 1.0 plug

Figure 21: CCS 1.0 vehicle inlet and the charging plug

Table 5: CCS/Combo 1.0

Parameter	Value
Connector:	SAE J1772 CCS 1.0
Voltage:	200 - 600 V
Current:	200 - 400 A
Power:	upto 240kW
Charge Level:	3

European Standards

June 2000, the European Commission issued the standardisation concerning the AC connector and DC connector for the European charging situation. The European charging system, inlet, and plugs follow the IEC 61851 standards. The European EV standards are indispensable to ensure EV drivers have enjoyable trip of long distance within Europe because of EU-wide charging system that fits all. The European government and the operating of charging station invested money to built and develop the charging infrastructure [31].

The rated power is divided into three categories: slow charging, medium or quick charging, and fast charging. The IEC 61851-1 Committee has classified the conductive charging connections into 4 different Modes.

Table 6: European charging Modes and ratings [26] [31]

Charging Mode	Voltage	Max Current/Power	Typical use
Mode 1 1 phase AC	230 V	10 - 16 A/3.7 kW	Slow charging for home/EV parking
Mode 2 1/3 phase AC	upto 400 V	63 A/ 43 kW	Medium charging for private/ public
Mode 3 3 phase AC	200 - 600 V	from 63 A/from 43 kW	Fast charging for public use
Mode 4 DC	200 - 1000 V	500 A/350 kW	Fast charging for public use

Mode1 charging system is used for slow charging at home or EV parking. The plug is does not need an extension cord. In some countries the Mode 1 is not in use anymore. The connection is a single phase AC voltage and the electrical installation should follow the safety regulation, for example the earthing line must be present, earth leakage protection and circuit breaker to prevent overload [24].

Mode 2 charging system is medium charging used for private and public. The connection can be connected with a single or three-phase AC voltage. The cable is specially built with the supply equipment, the regulation of this must follow the standard among those is according to IEC 62196 and communication signal according to IEC 61851. The charging cable for this Mode is usually included with the purchase of EV. The charging cable gives protective earth detection, in-cable RCD to prevent the electric shock, over-temperature, and over-current protection. The current does not exceed 63 A and maximum power of 43 kW.

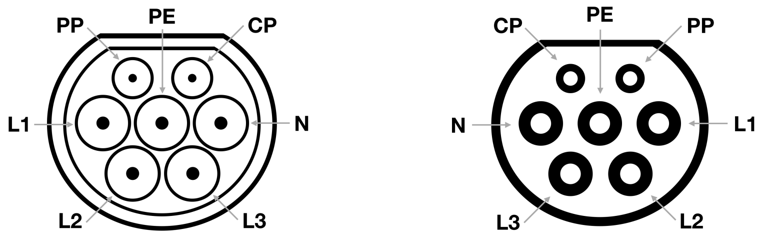
Mode 3 charging is for fast three-phase AC voltage, typically for public use. The vehicle is connected to the supply network through EV charging equipment that has a protection and control function built within. The power level is higher than Mode 2, but it has identical safety protocol as Mode 2.

Mode 4 is fast DC charging for public used. Electrical vehicle is connected with the charging station through socket outlet. This method is called for an off-board charging. Protection and control functions in built in the charging station and the vehicle. The highest power rate is 350 kW with max current of 500 A.

2.10.3 Mennekes Type 2

The EV charging in Europe using a different standard, so-called standard IEC 62196, which is analogous to SAE J1772 standard. The standard was selected by the organisation in the European Commission for the European Union country.

Type 2 connector is also known as the Mannekes connector after the company first proposing standard IEC 62196 [24]. As presented in Figure 22 for Mennekes connector is consist of 7 pins: earth pin, 3 phase pins (L1,L2,L3),earth pin, neutral pin, and 2 control pins which corresponding with IEC 61851-1. The control pins are Control Pilot (CP) and Proximity Pilot (PP) signals. The Control Pilot has a PWM signal to communicate with EV supply equipment. It also supports both single-phase and three-phase with higher maximum power output than Type 1.



(a) Type 2 vehicle inlet (b) Type 2 plug

Figure 22: Type 2 vehicle inlet and the charging plug

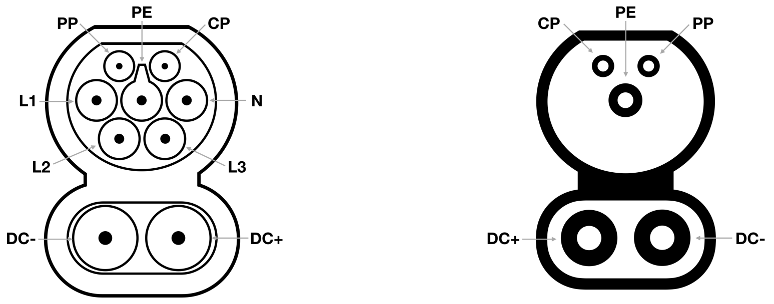
Table 7: Mennekes Type 2

Parameter	Value
Connector:	Mennekes Type 2
Voltage:	250 - 400 V
Current:	upto 63 A
Power:	43 kW
Charge Mode:	1 and 2

2.10.4 Combined Charging System (CCS) 2.0

The European Automobile Manufacturers (ACEA) is the organisations that have developed the CCS 2.0 charging standards [32].

The combination of SAE J1772 standard (type 2) plus DC voltage pins known as CCS 2.0 for use in the Europe. For this condition, the cable assembly is part of the charging station or off-board charging method. Moreover, this charging system should support both AC and DC charging built in one inlet in the vehicle. As seen in Figure 21, they added two large pins for dc high power. The power for DC charging is usually above 50 kW [30] and can have a maximum charging rate of 350 kW. There is still ongoing research for future development for even higher charging rate at the charging station infrastructure and more and more EV manufacturers consider using CCS as a charging system [32].



(a) CCS 2.0 vehicle inlet (b) CCS 2.0 plug

Figure 23: CCS 2.0 vehicle inlet and the charging plug

Table 8: CCS/Combo 2.0

Parameter	Value
Connector:	CCS/Combo 2.0
Voltage:	200 - 1000 V
Current:	upto 500 A
Power:	upto 350kW
Charge Mode:	2 - 4

The connector is consists of 5 pins: earth pin, 2 control pins, and 2 DC power pins DC+, DC-. Both CCS type is using the same physical pins for control and communication. The communication for CCS is using a Power Line Carrier Communication (PLCC) on CP pin. The PP should detect the plug is connected and CP has the communication with EV supply equipment. PLCC is a part of the smart grid protocol and using HomePlug Phy for the fast charging control systems. The communication standards for CCS 2.0 followed according to ISO/IEC 15118-2,3 and DIN SPEC 70121

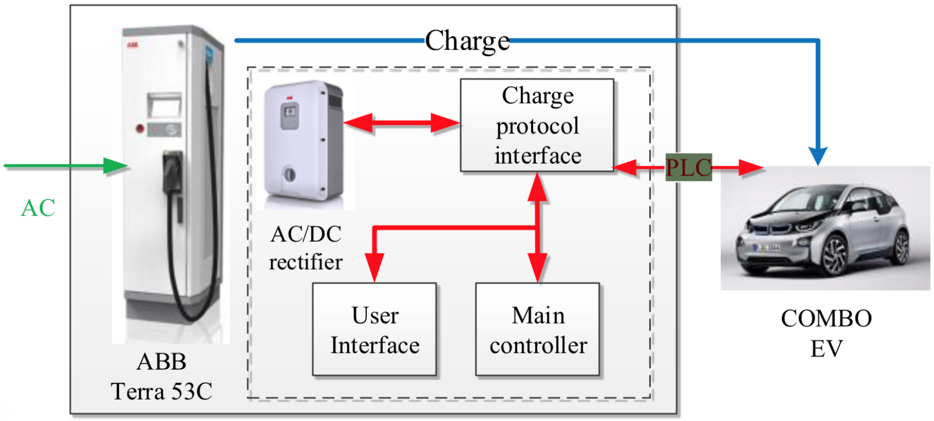


Figure 24: Example of CCS charging dynamic system using 50kW ABB Terra 53C charger [30]

2.10.5 SAE J1772 Signal

Later in the project case study chapter, the small scale laboratory experiments will be proposed, and the selected Level to do the small scale laboratory experiments was given to be an AC Level 2 of SAE J1772. Therefore it is necessary to look into the signalling circuitry before the experiments. The signalling circuit is shown in Figur 25

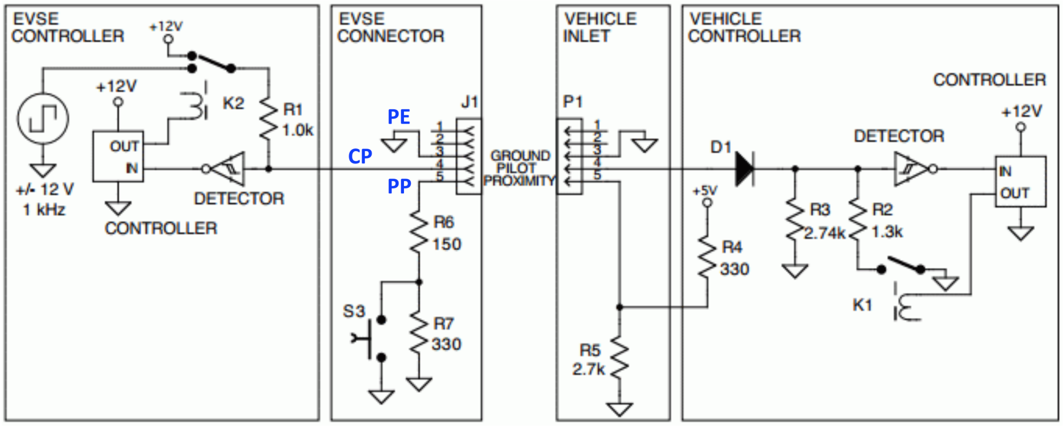


Figure 25: Schematic of signalling circuit for the J1772 standard [33]

2.11 Communication Protocols

2.11.1 Control Pilot (CP) and Proximity Pilot (PP)

In each charging plug has the Control Pilot (CP) pin and through the CP line, the PWM and Power Line carrier communication are both transferred over the CP line. Usually, the signals starting from the EVSE to the EV. The CP has the primary responsibility of sending the PWM signals to the EV. So whenever the plug is mated, the EV should able to read the PWM signal in the form of duty cycle, and it will know what the maximum of charging current the EVSE sending.

The EV can monitor and generate the duty cycle as the EV required in able to reach the maximum accessible current from EVSE. The EV should able to read the BSS condition based on the battery SoC and temperature of the BSS. The EV can request the current value to the charging station, which made the EV is the Master, and the charger will behave as a Slave. The EV is the one who is getting the current value it needs from the EV supply equipment. Gradually, when the current is near or less than the maximum limit, the EV requesting current less and lesser, and the SoC will be slower and slower. Therefore, it has been recommended to stop when the SoC is on 80 % because the rest of 20 % will take much longer time to fill [30].

The Proximity Pilot (PP) has the main task to detected the physical connection between the supply equipment and the EV simultaneous [29]. Together with CP and Protective Earth (PE), it will ensure the communication to operate at the maximum capacity of the EVSE to EV. It have the lock mechanism, and prevent the users to plug out the connector during the charging condition. Hence, minor error will occur. If there is an error, which may occur in the EV or the EVSE, the PP and CP will read it and prohibit the charging from starting.

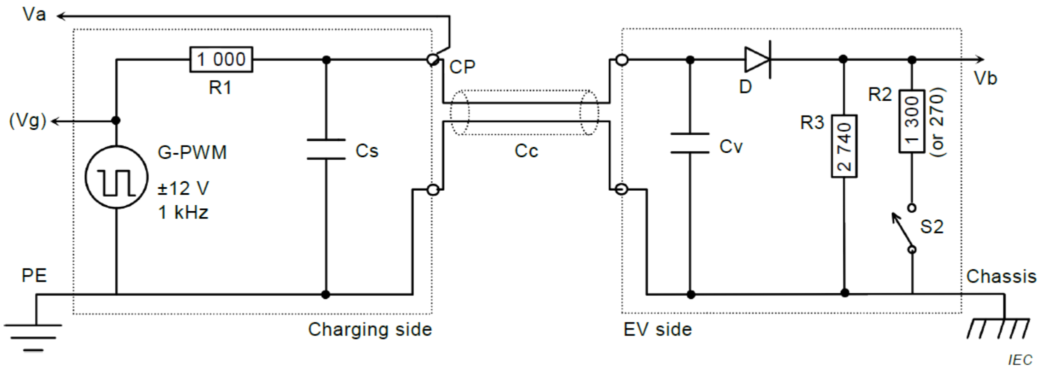


Figure 26: Control Pilot Circuitry [29]

Brief summer of the advantages of using the CP signal is by the following :

- To detect the protective conductor connection
- To detect the vehicle status, from beginning to the end. Whether the vehicle is not connected, connected, ready to charge, ventilation required and error.
- The transmission of the charging controller status, if it's ready, not ready or has an error.
- Via PWM signal or duty cycle on CP it will monitor the maximum available charging current value for the electric vehicle.

2.11.2 CCS charging flowchart

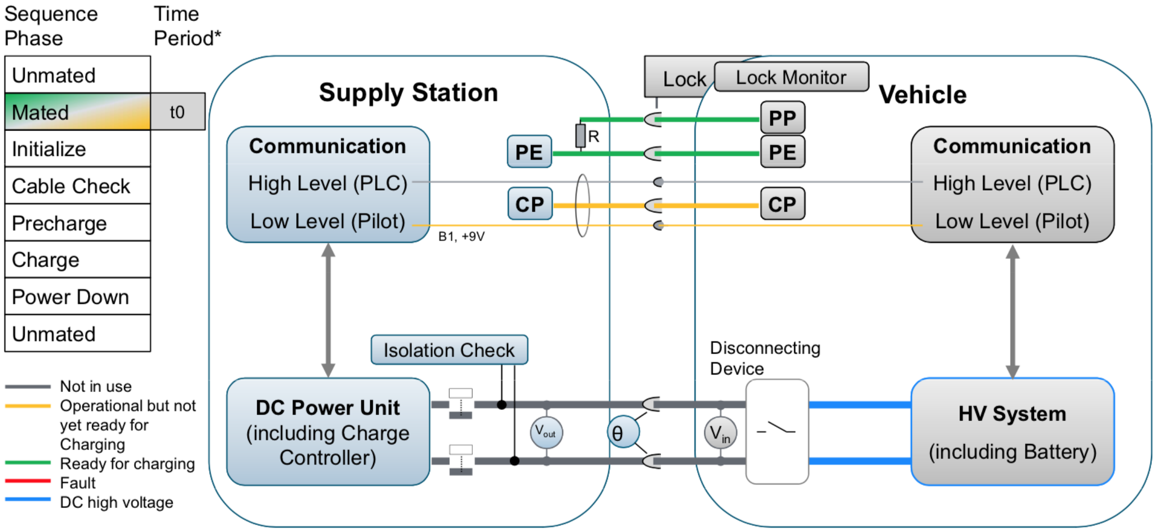


Figure 27: CCS architecture on system level

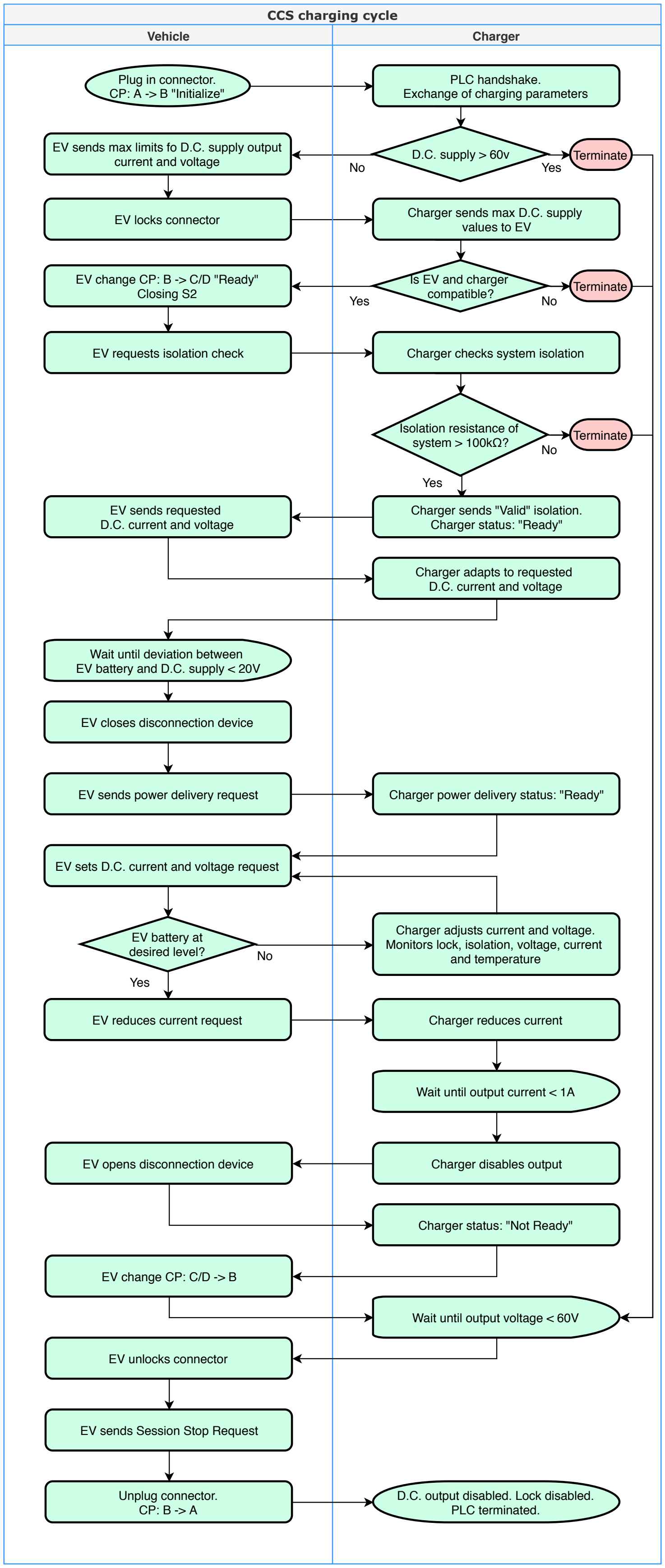


Figure 28: CCS Charging Cycle Flowchart

2.12 Vehicle to Grid (V2G) Energy Transfer

Using bidirectional DC-DC converter have made it possible for the EV to supply power back to the local grid and the method known as vehicle to grid (V2G). It is usually using a Microgrid operation. A Microgrid operation is a term for a local power grid, and it can be connected to the main power grid. It can also be disconnected to the main power grid if the need for independent operation occurs [1].

V2G technology proposed of using batteries in the EV as distributed storage devices and provide the energy to the grid. The technology is still under the study.

3 Power Electronic Interfaces

3.1 Power Electronics

To have a proper understanding of EVs, it is necessary to know the working principle of the power electronics topologies. There has been a significant improvement in power generation, high-efficiency power electronics and electric propulsion systems with DC architecture in addition to the new trend in the EMVs.

The design of communication protocols of the selected charging standard and control unit for the EMVs is composed of the power electronics, hotel electric auxiliaries, battery storage system, and an electric motor. The type of converters for the electronics appliances in the vessel, depends on individual requirements from case to case. There are numerous converter types and topologies that are excellent to use in the electric propulsion system.

The benefits of using the switch mode on and off in power converters are to reduce the total harmonic distortion and to correct the power factor. The requirement to interfacing of energy storage with the load and power source in a smart way which will increase the reliability and efficiency to the system [34]. The ability to set the limitations of the injected harmonic current and power factor as required, with the purpose to upgrade the electric grid efficiency and increase real power utilisation.

3.1.1 Super-Capacitors

Super-capacitors are commonly used to maintain the high startup current, and are around 10 - 100 times better than the battery and it has high current density. It depends on what type and rated power of the motor is being selected for the vessel, in [11] the motor have the rated power 20 kW, and during the startup, it can rise to 4 times higher. Super-capacitors is an excellent choice to implement for correctly saving the startup energy. It only requires approximately 5% of battery capacity. Since the super-capacitor is more efficient than a battery pack, which has made them expensive compared to the battery price and therefore it is not necessary to install more.

3.1.2 AC-DC Converter

AC-DC converter, also known as a rectifier, is used to make the voltage and current positive when they are in the negative half cycle [1].

3.1.3 DC-DC Converter

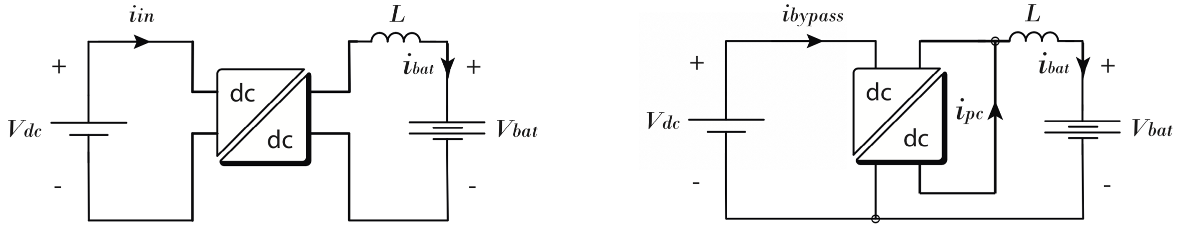
DC-DC converter is an electronic device used to convert low voltage level to higher voltage level and the opposite. Buck converter and Boost converter is a type of DC-DC converters and also known as a switching converters [35].

- Boost converter have the characteristics such as the output voltage is greater than the input voltage and the value is positive. The input current is depends on the switching frequency and the input inductance value.
- Buck converter is step down the voltage level, it has two switch (transistor and diode).

The DC-DC converter has been used in several modern technologies, such as in battery charger, MPPT, DC motor drive and LED drive [36]. The use of a DC-DC converter for battery charging in EMVs is important for managing the flow of electrical power and improve the efficiency to realise the performance as desired.

There are also some challenges when using a DC-DC converter, such as high current ripple and switching losses. Therefore it is necessary to use the right filter, such as an LC filter to able to reduce the current ripple and using modern transistor technologies to reduce the switching losses. With those handled, then the efficiency will increase [37]. A traditional DC-DC converter can be transformed into a bidirectional converter using the bidirectional switch by using MOSFET or IGBT in anti-parallel with diode.

A study in [38] which has proposed the use of a Partial Power Converter (PPC) for DC-DC conversion stage of EV's fast charging station. By implementing the converter topology that based on the dual H-bridge DC-DC converter. The PPC will regulate by allowing the converter to process only 36% of total power, and letting the rest of the power flow directly to the load. The result of only allows a part of the power that flowed through the converter gives benefits that are more efficient compared to if it was a full power that flowed through the converter. Among it is less switching and magnetic losses, reduction of the conduction and efficiency risen from 95.1% to 98.3%.



(a) Full power DC-DC converter (b) Partial power DC-DC converter

Figure 29: DC-DC conversion for fast charging station [38]

3.1.4 Bidirectional DC-DC Converter

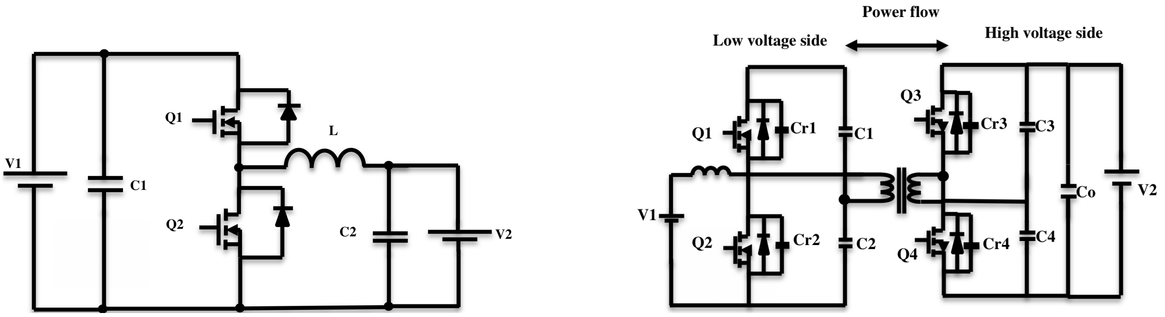
Bidirectional DC-DC converter has a significant role in electric vehicles technology. They cover the requirement of power connection from the source to the battery or super-capacitor as a load or so-called battery storage system (BSS) in the EV. The bidirectional DC-DC converter is used to capture the kinetic energy of the motor and charge the battery through regenerative braking. It is also used to smooth the power flow to BSS and power conditioning, which will improve the quality of the power delivered to the load and increase the efficiency of the charging system [34].

The device has the switch on and off capabilities at high frequency, for example in Dual Active Bride (DAB) and Isolated bidirectional DC-DC converter that will provide both savings of the surplus energy, galvanic isolation, and efficient power flow, without wasting the energy. In able to study further into electric vehicles, it is essential to know about the working principle of the DC-DC converter.

To control the charging and discharging of the battery storage system, it is necessary to use a bidirectional DC-DC controller. By choosing a modern converter which has the possibility to operate between two fixed voltages, the battery storage system voltage and the DC bus voltage. A bidirectional DC-DC converter is implemented with two PI controllers with two different value of the gain, one value for the charging process and other value for the discharging process to achieve the desired reference current signal. The battery charger controller must correspond to voltage and current reference signal for charging and discharging, also possible to regulate the DC bus voltage when it is necessary [39].

Nevertheless, the current ripple can be a challenging with the bidirectional DC-DC converter, by reducing the current ripple, it will give higher efficiency and a longer lifetime to the batteries. It will also give an economic benefit for the owner of the maritime electric vessel if the battery system going to last much longer than expected. The following equations that can be used when selecting the values of the current and voltage.

There are two types of Bidirectional DC-DC converter is shown in Figure 30.



(a) Non Isolated Bidirectional Buck-Boost DC-DC converter

(b) Dual Half Bridge (DHB)- Isolated Bidirectional DC-DC converter (IBDC)

Figure 30: Bidirectional DC-DC converter

Non Isolated Bidirectional DC-DC converter (NIBDC) The non-isolated bidirectional DC-DC converter can provide electrical isolation between source and load without using a high frequency transformer. Due to safety reasons, these are not recommended to use in high power application. The advantages of this type of converter are easy to control, simple to design and have low weight because it does not use a transformer. Example of this converters are Bidirectional Buck-Boost converter, Bidirectional CUK converter, Cascaded Bidirectional Buck-Boost converter, Half-bridge bidirectional converter, etc. Bidirectional Buck-Boost converter has been used in EV applications because the topology is simple and have high efficiency. As shown in Figure 30a, it has two switches, and those are operating in anti parallel according to the duty cycle. The circuit consists of the combination of buck-boost converters. Q1 is conducting during the boost mode, and Q2 is not connected. The opposite, when Q2 is active than Q1 will not conduct [34].

Isolated DC-DC converter (IBDC) There are many topologies of isolated converters, among those are Dual Half Bridge IBDC and Dual Active Full Bridge IBDC. How IBDC work is by using a high-frequency transformer to ensure galvanic isolation. It is primarily to have the galvanic isolation to avoid the overload condition for EMV. Another benefit of galvanic isolation is to reduce the noise and for voltage matching between different conditions. This type of converters has two stages, and those stages connected through a high-frequency transformer, the first stage is DC-AC and second stage is AC-DC.

Dual Active Full Bridge IBDC are more suitable choice, use in hybrid energy system and will not be further considered for this thesis application. Dual Half Bridge IBDC in Figure 30b have also been used in EV applications. Isolated DC-DC converter will provide the safety standard of galvanic isolation. Dual half bridge IBDC is an excellent converter to implement in EMV, include with their high power density, soft switching technique, and simple control technique. However, it also has a disadvantage, which is heavy in weight because of transformers.

Transformer is used for safety improvement and efficiency in power regulation. It can transfer the electricity between the circuits with the same frequency but changing in the voltage level.

DC-link is an electrolytic capacitor that can be used to filter the 50/60 Hz component.

4 Laboratory test

A small scale laboratory test was proposed to verify the aforementioned theory and build a foundation for a full charger setup. For simple communication and control there are two Wago PLCs, one for the charger and one for the EMV. An EV charging controller board is also used, as well as two PLCC units. e!COCKPIT, dSPACE and Matlab Simulink is used to program, monitor and control the equipment. A sketch of the proposed setup can be seen in Figure 31.

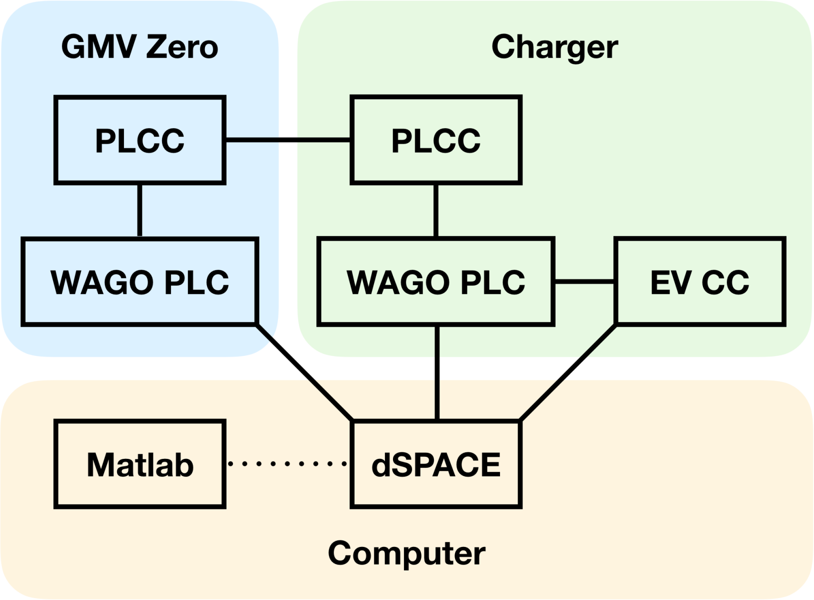
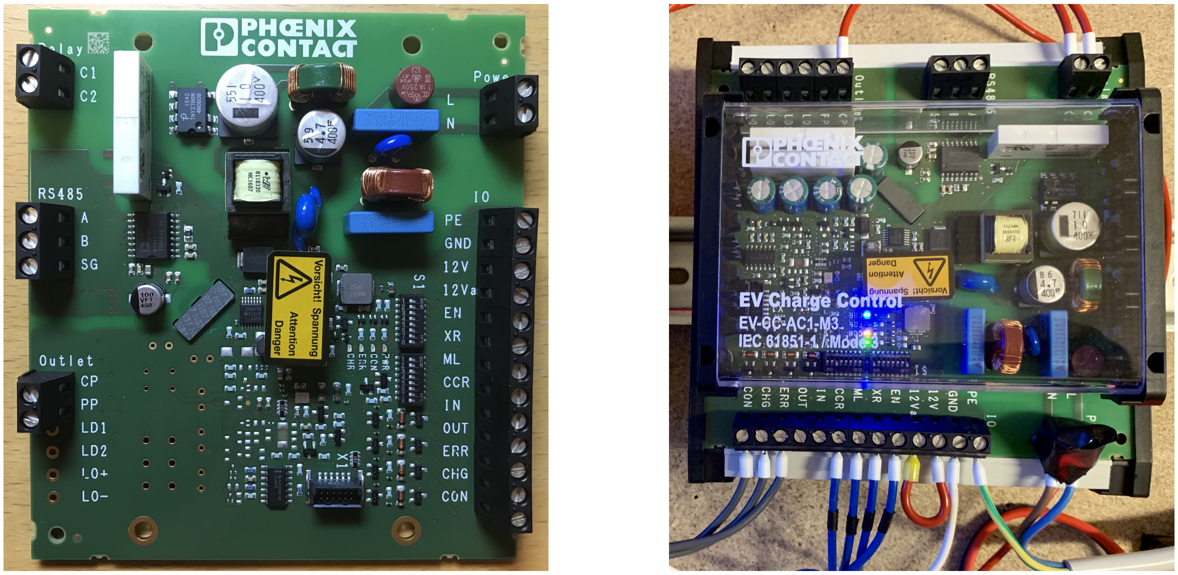


Figure 31: Sketch of the proposed test setup

4.1 Charging Controller (CC)

Several charging controller boards were evaluated for the project. In the end the decision fell on series EV-CC-AC1-M3-CBC-SER-HS (1622452) [40] as a Printed Circuit Board (PCB) to control and monitor the charging behaviour of electric maritime vessel. This card was chosen for its capabilities, price and availability. The controller is operating as Mode 3 according to the product specification and it follows the IEC 61851-1 standard. Moreover, it shall also run as AC level 2 charging according to SAE J1772. For the powering it needs 230 V AC power supply, which can be obtained by plug into a wall socket in the laboratory. Hand made 230 V cable with three different output wire, that can be inserted into L, N, and PE in the terminal box on the charging controller PCB.

In able to monitor and control the charging of the EMV, the charging controller can be implemented inside of the infrastructure on the power grid side. The function is to control the switching element during the connection between the EV or in this case, the EMV and the grid. Through the charging controller, it will be examining the communication interface of Control Pilot (CP) and Proximity Pilot (PP) signals.



(a) First tested EV CC board series 1622460

(b) Second tested EV CC board series 1622452

Figure 32: Tested EV Charging Controller Series

4.2 Simulink emulation of Control Pilot PWM Signal

When experimenting with the EV CC board an accident caused some of the components to fry. The board was an open PCB and a lose wire cased a short circuit between the high voltage and low voltage side of the board. A new board with protective case was ordered, but the delivery time was uncertain, which meant an alternative solution had to be found in case the new board was delayed.

The solution was to emulate the CP signal of EV CC board in dSPACE. The signal along with the CP control circuit was modelled in Matlab and transferred to dSPACE. The model can be seen in Figure 33.

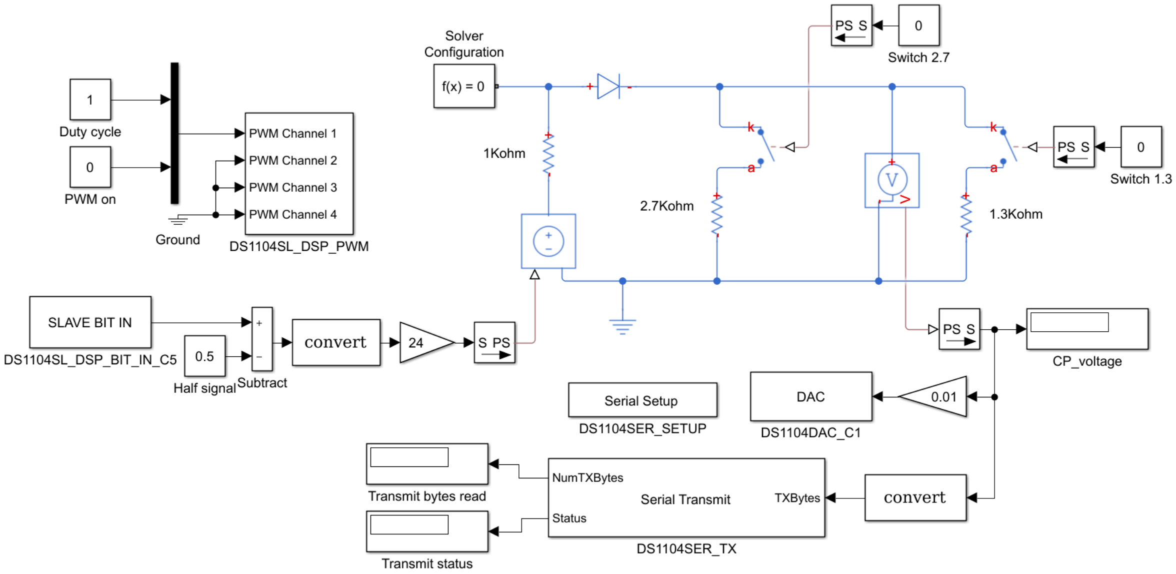


Figure 33: MATLAB model of PWM on CP

It starts by generating a pulse width modulated signal with 100% duty cycle on PWM channel 1. This is outputted on pin 5 (ST2PWM) of the slave I/O PWM modulation connector (CP18) on RTI 1104 interface. The output is physically wired to input pin 24 (ST3PWM) which can be seen as the slave bit in block to the left in the model. The PWM signal comes in with low value of 0 and high value of 1. The CP signal should be $+/-12$V so first 0.5 is subtracted and then the signal is multiplied by 24. This now perfectly emulates the CP signal.

The CP signal is used as input to a voltage generator. There are two resistors in parallel with the generator; a 2.7kΩ and a 1.3kΩ. Both of the resistors are in series with their individual switch. The switches are controlled from dSPACE control-desk. Based on the switch setting and the resulting circuit, the CP signal is altered. The resulting signal is divided by 100 and outputted through the DAC channel 1 and into an oscilloscope. On the oscilloscope it was confirmed that the CP signal behaved the same way as on the physical board. Figure 34 shows the oscilloscope readout at both PWM channel 1 and DAC channel 1. There was also an attempt to transfer the signal by serial interface to the PLC, this is further discussed in section 4.5. In the end, this emulation was not used as the new EV CC board arrived on time.

Figure 34: The emulated CP PWM signal from oscilloscope

4.3 Programmable Logic Control (PLC)

Programmable logic controller (PLC) is a type of computational device that was invented in the late 1960s to replace relay control systems [41]. As the name implies, it can execute logic code based on AND, OR, NOT, Timers, and a whole lot of other functions. One of the strengths of a PLC is the number of inputs and outputs they can be configured with. The largest can have over a thousand inputs and outputs. They are also very robust and are built to withstand harsh environments. PLCs are widely used in industrial automation like car factories or offshore drilling platforms [42].

The Wago-system 750-8102 is the PLC that is going to be used in this project. It comes with a serial port for RS232 or RS485 communication, and also two Ethernet ports. To program the Wago PLC, one must use their e!COCKPIT software. It can be programmed with many different languages; structured text, ladder, function chart, instruction list or function block diagram. Both statement list and function block diagram are used here. Statement list offers the most powerful programming, but it is also the hardest to program. Function block diagram is a graphical programming languages and have less capabilities, but are easier to program and troubleshoot for novices.

A PLC will repeatedly execute its program in cycles at fixed intervals. The cycle time, or how long the PLC takes to execute the code one time, is typically between 1ms and 10ms depending on the speed of the PLC and the complexity of the code. The interval, or interrupt time, is set by the programmer and usually between 10ms and 100ms. The interrupt must be set higher than the cycle time otherwise the PLC will not be able to execute the full code. In this project the interrupt is set to 10ms on each PLC and the average cycle time is measured to 0.5ms

PLCs are used instead of PCs for several reasons. They are designed to execute the programmed code, and nothing else, making them very reliable. A PC running Windows is a multipurpose machine and the operating system will run commands in the background that may interfere with the performance. In terms of robustness, a traditional PC is inferior to a PLC which is designed from the ground up to industrial applications. However, PCs can also be manufactured to be just as robust as a PLC, and they can run special real-time operating systems with little interference [43]. As mentioned earlier, a PLC runs both graphical and text based code, while a PC is programmed with C, C++, Python, and Java among others. The PC programming languages can be challenging to troubleshoot as the code is running. You may print variables at various points, but this requires code change and you must also know which variable to print and where. In the PLC code on the other hand, you can go in an monitor all signals and values while it is running, making troubleshooting much easier.

When looking at it from a cost perspective we see that for simpler applications that the PLC offers cheaper performance, higher expandability, better environmental protection, and less development time [44]. However, for large and complex projects, the PC becomes a much more viable option to use.

4.3.1 Voltage Divider

In the progress of the thesis case study, where one of the setups is to connected the PLC system digital input (DI) and digital output (DO), and the EVCC board to be able to transmit and receive the signals either way. From the data specification, the PLC system has 24 V and the EVCC board has 12 V. There is a difference in voltage between those two. From the PLC DO, the voltage needs to be reduced to 12 V and it can be solved by using a voltage divider.

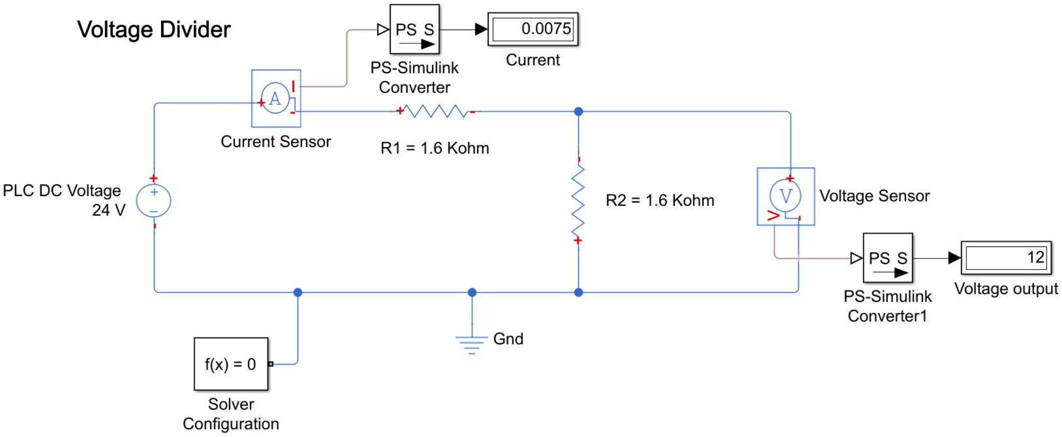


Figure 35: MATLAB model of voltage divider

Voltage divider has been designed in Matlab model and 4 physical models on the breadboard. The voltage output is slightly different, 12 V in the Matlab model and approximately 11,70 V from the physical model, nevertheless it will not give any influence for the communication between the systems. A small error from the components is to be expected. The current is same in the circuit, the voltage across both resistor of a series circuit can be derived by Formula 2 of the voltage-divider rule [45].

$$\begin{aligned} I &= \frac{E}{R_T} = \frac{V_{PLC}}{R_1} = \frac{V_{out}}{R_2} \\ V_{out} &= V_{PLC}\frac{R_2}{R_1 + R_2} \end{aligned} \tag{2}$$

4.3.2 Optocoupler

An optocoupler is normally used for transferring a signal from one electrical circuit to another without having a physical connection, thus eliminating noise. It works by energising a LED on one side which is then recognised on the other side. The signal is transferred by light and the two circuits are thereby electrically isolated from each other. In this project optocouplers are used as switches. By connecting the LED side to dSPACE or PLC output, it can connect the circuit on the other side to ground when needed.

4.4 Power Line Carrier Communication (PLCC)

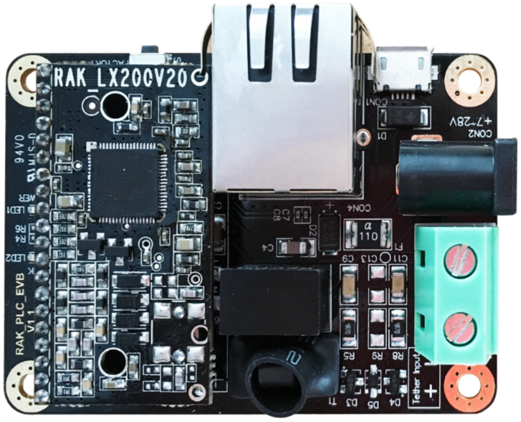


Figure 36: WisPLC Pro [46]

The power line carrier communication (PLCC) that is going to be used for the laboratory setup is WisPLC Pro. It has maximum transmission rate up to 500 Mbps, comes with an Ethernet port and support the twisted pair interface. It does not need any user configuration, simply plug and play.

In general PLCC is one of many communication technologies that exist today. The most known areas is related to communication for the smart power grid and home network. The demand for the various bus systems in the automotive industry continues to rise for every year [47]. Moreover, the PLCC has proven to give great benefits regarding costs and weight reduction. The wiring infrastructure has a significant role and found to be the third factor that contributes to the overall weight. Such as in a large ship, it has been more than 20% of the total weight is caused by electric cables. The increase in weight has a negative impact on the performance and the efficiency of the vessel. Therefore, the PLCC is considered as an excellent choice for the communication technologies that will reduce the amount of wiring. Less cost, less weight and more efficient [48].

Currently, PLCC has been implemented in most hybrid and electric vehicles, for operating with different tasks. One of many tasks is for charging communication, from the moment the socket outlet is mated on the vehicle to the end of charging cycle. The demand to recharge the battery both in slow and fast charging. The study of this technology in an electric car is still new and have an essential potential development for technology advances [49]. It now has a great potential to be implemented in electric maritime vessels. The charging connector which use PLCC technology is CCS, which is the selected charging standard for this project. The purpose is to serve as a smart communication between the grid and EMVs. The data exchange needed for diagnosis of the grid to ensure the charging flow of the power delivery into the EMV battery charging system and make it more reliable.

PLCC technology is based on the HomePlug Green PHY (HomePlug GP) protocol and is chosen for low power use application, where it can quickly adapt with an existing in-vehicle

12 V battery [50]. It uses smart electronic components that provide high-speed data transmission over the existing control pilot cable between the EV and the charging station that has the CCS infrastructure socket outlet. It converts the CP into a data line via the superposition of a low power information signal to the power wave, which carries both data signals and pulse width modulation signal simultaneously.

In General, there are two types of PLCC: broadband frequency spectrum (BB-FS) and narrowband frequency spectrum (NB-FS). According to [51], the kind of PLCC that fits to implement into CCS communication is a broadband communication. Which means narrowband communication will not be able to support the required HomePlug GP communication protocol on the pilot line. In the BB-FS PLCC signals can be operated from 1.8 MHz up to 86 MHz and have the possibility to streaming high-speed multimedia content [48] [52]. The HomePlug GP has defined to run at the frequency from 2-30 MHz for energy efficient transmission.

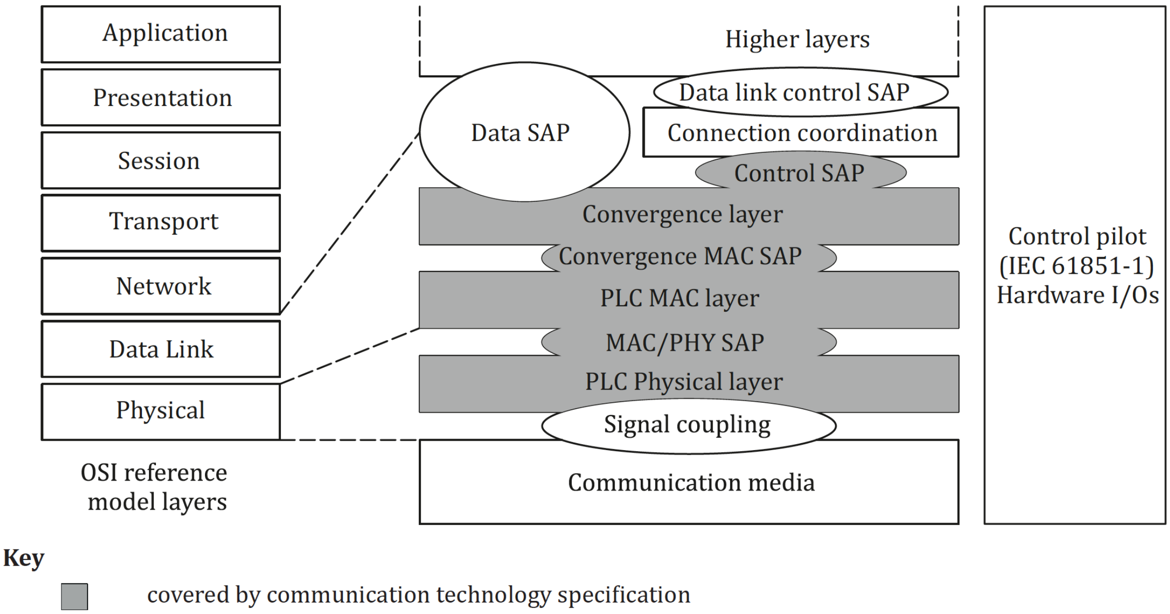


Figure 37: Communication stack for CCS charging [53]

The PLCC communication stack in ISO/IEC 15118-3 consist of many layers. At the very bottom is the communication media as seen in Figure 37, which is the CP cable. The signal coupling is how the signal is connected to the cable. The physical and data link layer marked in grey are part of the G3-PLC-PHY and G3-PLC-MAC specifications. The MAC address is a unique network identifier for each board.

Figure 38 shows how the PLCC unit should be implemented in the CP control circuitry. Item 5 on each side of the drawing are the locations of the two PLCC units on the charger and EMV side respectivly.

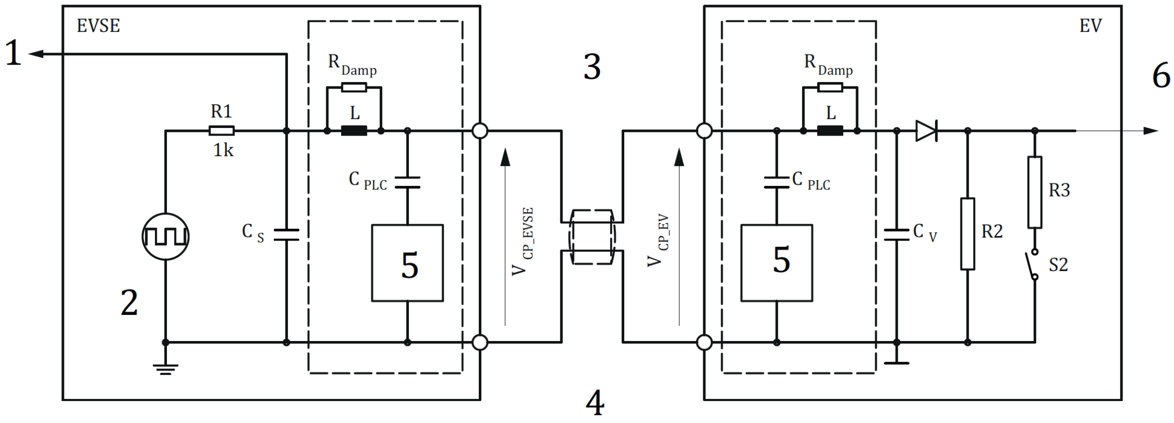


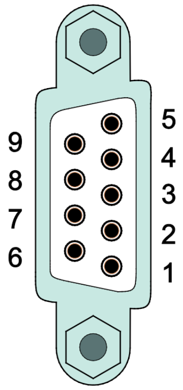
Figure 38: PLCC placement in CP circuitry [53]

4.5 Serial Interface

A serial interface is a type of communication that is most used in electric equipment today. The purpose is to provide a single path for data transmission over a cable or wireless, and this project will only consider a cable connection. It is also has been developed in serial interface technology with higher data transmission speed and capability to have multiple devices connected for practical applications. A possibility to communicate when there is a certain distance located. The process is consist of a transmitter and the receiver end. Furthermore, the data is sent one bit at a time, sequentially, to/from a computer bus or communication channel.

The original serial interfaces that are actual to use in this project is RS-232 or RS-485 protocols since they are the most common used today. For the further development of this project, its a needed to use one of those mentioned protocols, to provide the standardized of logic levels from transmitters to receivers for the flow of the charging cycle. The data rates and time and be specified as required. In some cases, they can perform a parallel-to-serial and serial-to-parallel conversion or specify a data protocol. The definition of logic levels, medium, and layer 1 of the Open Systems Interconnection (OSI) or connectors that is part of the physical layer (PHY) networking model.

4.5.1 PLC Wago I/O System



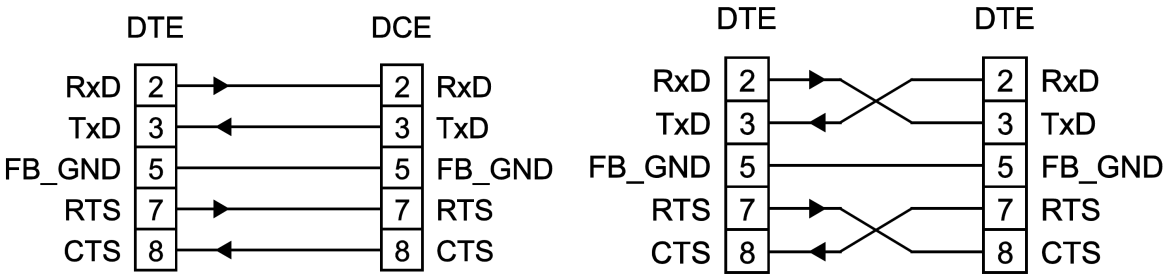
RS-485		
Pin	**Signal on PLC**	**Description**
1	NC	Not connected
2	NC	Not connected
3	RXD/TXD-P	Receive/transmit data
4	NC	Not connected
5	FB-GND	Ground
6	5V	Power Supply
7	NC	Not connected
8	RXD/TXD-N	Receive/transmit inverted data
9	NC	Not connected

Figure 39: D-sub 9-pin female and signal connection of RS-485

As shown in Figure 39, the PLC Wago-I/O-system has D-sub 9-pin female of RS-485 communication standards and signal connection according to their descriptions. The voltage levels are from -5 V and +5 V. It is important to ensure the communication partner matches the signals.

Table 9: D-sub 9-pin female and signal connection of RS-232

RS-232		
Pin	**Signal on PLC**	**Description**
1	NC	Not connected
2	RxD	Receive Data
3	TxD	Transmit data
4	NC	Not connected
5	FB-GND	Ground
6	NC	Not connected
7	RTS	Request to send
8	CTS	Clear to send
9	NC	Not connected



(a) DTE and DCE straight wiring (b) DTE and DTE crossed wiring

Figure 40: Data Terminal Equipment (DTE) and Data Communication Equipment (DCE) wiring when operating as RS-232 interface

The primary protocol that is implemented in Wago I/O System is RS-485, thereby it is not necessary to be configured and it possible to use only a straight cable. Nevertheless, there is also an option to operate as RS-232 protocol instead, but it needs to configure before use. The configuration can be done by connecting as it showing in Figure 40 accordingly as the proposed.

4.5.2 dSPACE CLP1104 Panel

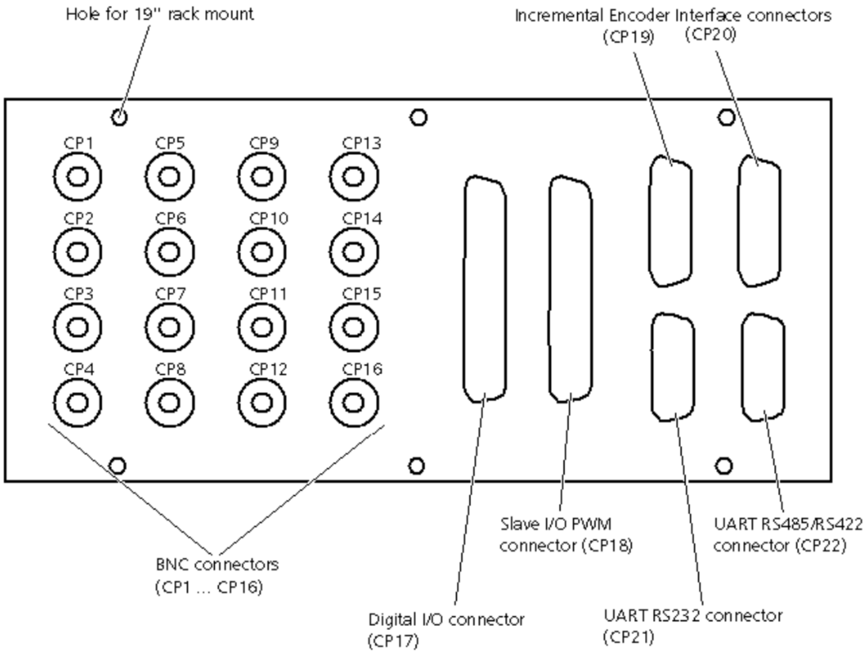
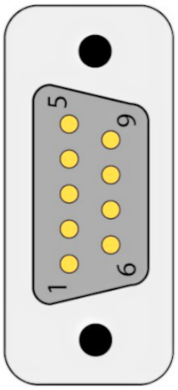


Figure 41: The dSPACE CP1104 connector panel overview

The communication standard on dSPACE is UART RS-232 and RS-422, to have a suitable performance when communicating. As mentioned above, the data must meet the same standard in each side to have stabilised communication and less error when operate. The dSPACE connector panel has UART RS-422 D-sub 9-pin male, which means it needs to be configuring to RS-485 protocol in order to communicate appropriately with PLC Wago I/O System RS-485 connector.



RS-422		
Pin	**Signal on dSPACE**	**Description**
1	TXD-N	Transmit inverted data
2	TXD-P	Transmit data
3	RXD-P	Receive data
4	RXD-N	Receive inverted data
5	GND	Ground
6	RTS-N	Ready to send inverted data
7	RTS-P	Ready to send
8	CTS-P	Clear to send
9	CTS-N	Clear to send inverted data

Figure 42: D-sub 9-pin male and signal connection of RS-422

When configuring from RS-422 to RS-485, the wire of transmitting and receiving data need to be joined together. The positive data with positive data and negative data with negative data or so-called inverted data. It is also important the wire is connected with the resistor to warning the data signal is near at the exit of transmitting and receiving wired, to avoid confusion for the data and give less error.

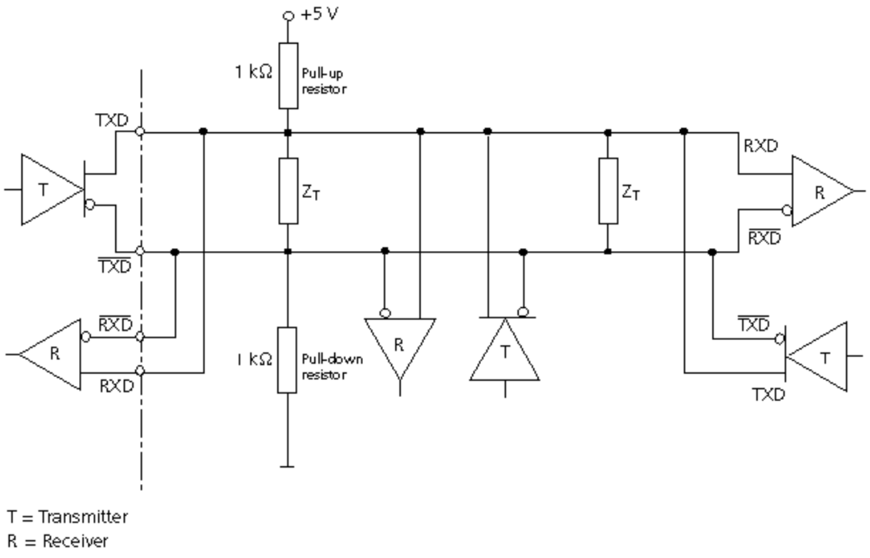


Figure 43: Wiring configuration from RS-422 to RS-485

4.6 Experimentation's of The Serial Interface

The serial interface is a way to communicate for the computer network. The process of the communication is to send a data bit one at a time, sequentially, over a computer bus or communication channel. The part of the project is to establish communication between the software and hardware to create a control algorithm. The setup is between PLCs and dSPACE. The interaction between those two needs to be completed, in order to build the control algorithm for the charging system for the next step. The e!COCKPIT software is going to be used for controlling the PLC , and the other software is MATLAB and Simulink which going to be implemented into dSPACE control-desk.

First chosen of serial communication protocol has been decided, where the RS-485 has been used. The RS-485 is the most commonly used for the PLCs because it is already implemented as RS-485 and supporting multiple commanding devices, and pin-out wiring is less complicated since they are only using two wire system. Fortunately, there has been unexpectedly challenged to get communication between the PLCs and dSPACE to work, and various experiments been tested to verify where the problem is. Below is an overview of different type of connections, communication protocols, and the result for the following attempted.

Table 10: Experiments of the serial interface

Serial connection and protocol testing				
No	**Connection**	**Protocol**	**Wiring**	**Result**
1	dSPACE to PLC	RS-485	Straight	Failed
2	dSPACE to PLC	RS-485	Joined	Failed
3	dSPACE to PLC	RS-232	Straight	Failed
4	dSPACE to PLC	RS-232	Crossed	Failed
5	dSPACE to Oscilloscop	RS-232	None	Worked
6	PLC to dSPACE	RS-485	Straight	Failed
7	PLC to dSPACE	RS-485	Joined	Failed
8	PLC to dSPACE	RS-232	Straight	Failed
9	PLC to dSPACE	RS-232	Crossed	Failed
10	PLC to PLC	RS-485	Straight	Worked
11	PLC to PLC	RS-232	Crossed	Worked

As it is shown in Table 10 above that, the connection between two PLCs has been found out to be working. Where it also indicates they are working correctly both with straight RS-485 wiring protocol and with crossed RS-232 protocol. Moreover, the connection between dSPACE to the oscilloscope is also found to be working. Means the oscilloscope is able to capture the data signal that dSPACE sending through the connector of the RS-232 protocol. Fortunately, the oscilloscope is not able to capture the data from the connector of the RS-485 protocol because of their limiting function.

Nevertheless, the combination of serial connection from dSPACE to PLCs and the opposite does not support each other. Neither dSPACE or PLCs are receiving any data. Since there is a lot of failed results of multiple connections and serial protocol test. In addition to, it has consumed much more time than expected to these experiments, therefore the serial communication between dSPACE and PLCs is not possible at this point as it will take too much time and resources.

4.7 OPC

OPC stands for Open Platform Communications and is a standard that was developed to ease the transfer of data between PLCs, HMI systems and PCs [54]. The standard was first released in 1996. There have been many versions of OPC since it was first invented. There is OPC Data Access, OPC Historical Data Access, and OPC Alarms and Events. These have all needed their own server and client software to work. In 2008 however, the OPC foundation released OPC Unified Architecture [55]. It combines all previous OPC standards into one and adds a lot of new functions at the same time.

OPC UA servers can broadcast on the network to make itself easily discoverable by clients. It automatically sorts all the data in a hierarchy to accommodate both large and small projects. Read and write permissions can be set individually for each signal and it has support for subscription and event-based signal transmission.

The Wago 750-8102 PLC has built-in functionality to act as an OPC UA server. When programming, it is possible to select which signals should be accessible in the OPC. Matlab 2019a has support for OPC UA and are thus able to read and write data to an OPC UA server [56]. By using an ”Interpreted Matlab Function” block in Simulink, it is possible to integrate OPC UA data from the PLC in a Simulink model. Siemens had already created such a function for using Matlab with their PLCs [57]. With a little adjustment, it was possible to use it for the Wago PLCs as well.

4.8 The final setup

The laboratory test setup went through many iterations over the course of the master thesis. It was gradually expanded as each test were complete. Parts had to be replaced as they broke and alternative solutions were tested. In the end there is a working prototype that is close to the proposed setup, with some compromises and improvements. There is still two wago PLCs with two PLCC units connecting the Ethernet interface between them. The EV CC board is connected to the charger PLC. Matlab is used to test, control and simulate the charging. Matlab communicates with both PLCs by use of OPC UA over Ethernet. A sketch of the setup can be seen in Figure 45 and a detailed schematic can be seen in Figures 44, 46 and 47.

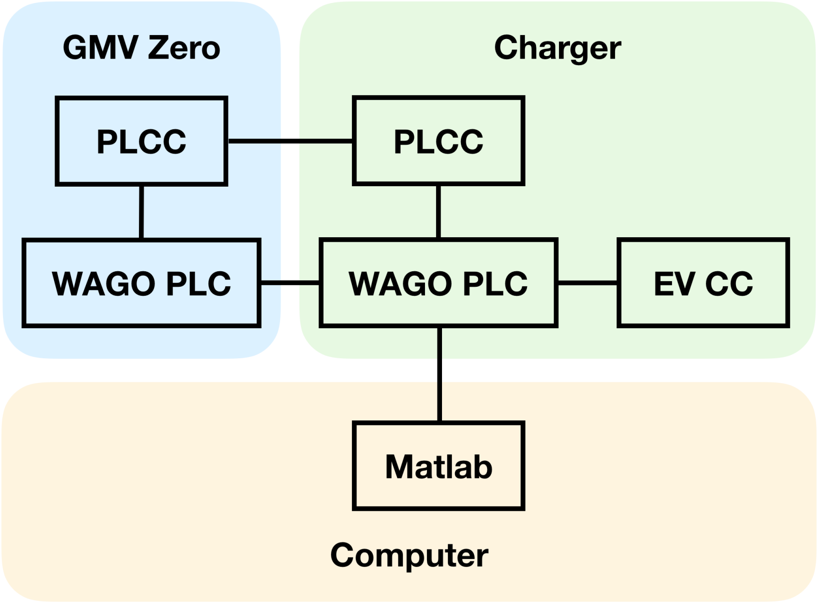


Figure 45: Sketch of the final test setup

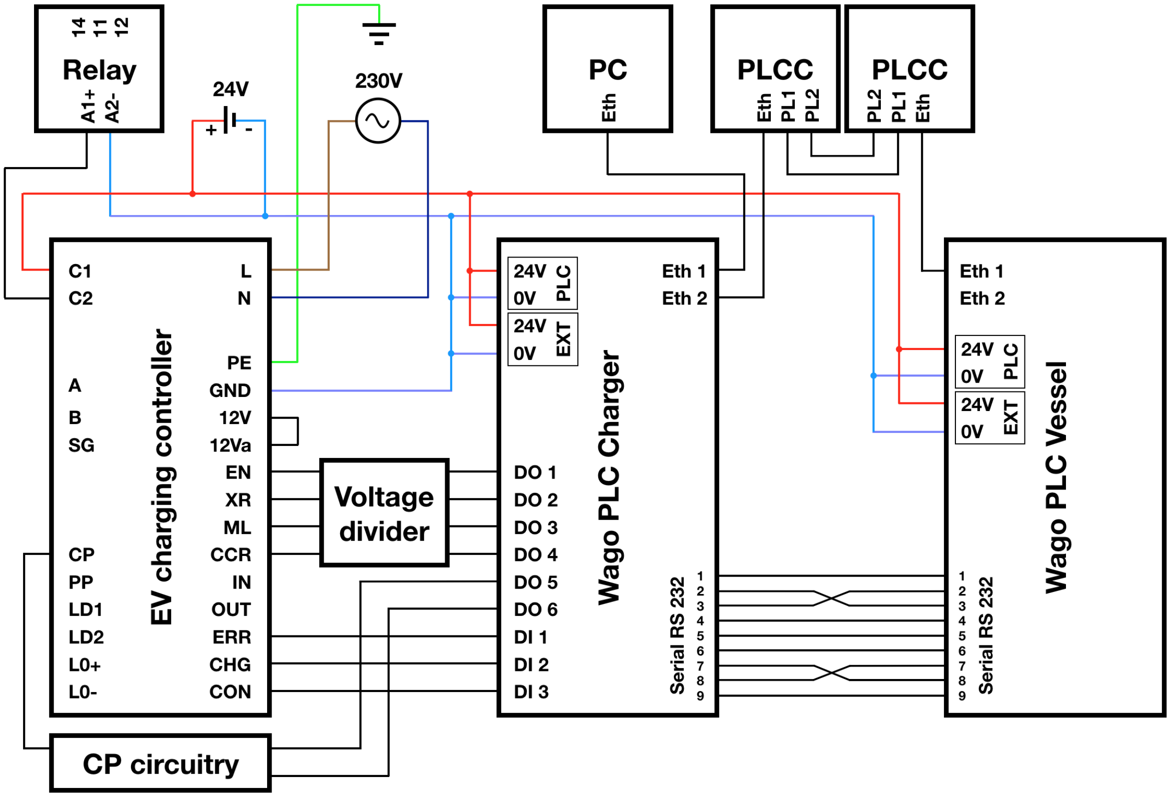


Figure 44: Schematic of the final test setup

The communication between the two PLCs should ideally be over Ethernet through the PLCCs. When trying to automatically configure this in e!COCKPIT however a bug caused

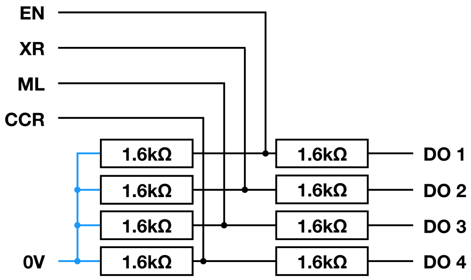


Figure 46: Schematic of the voltage divider

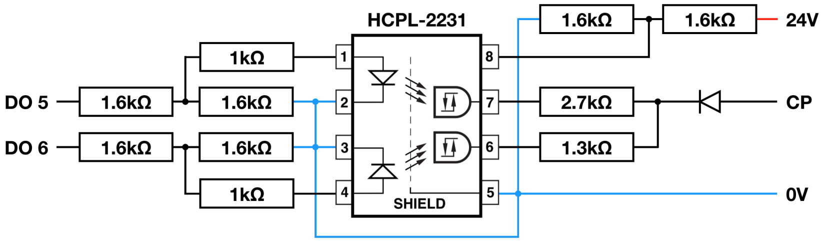
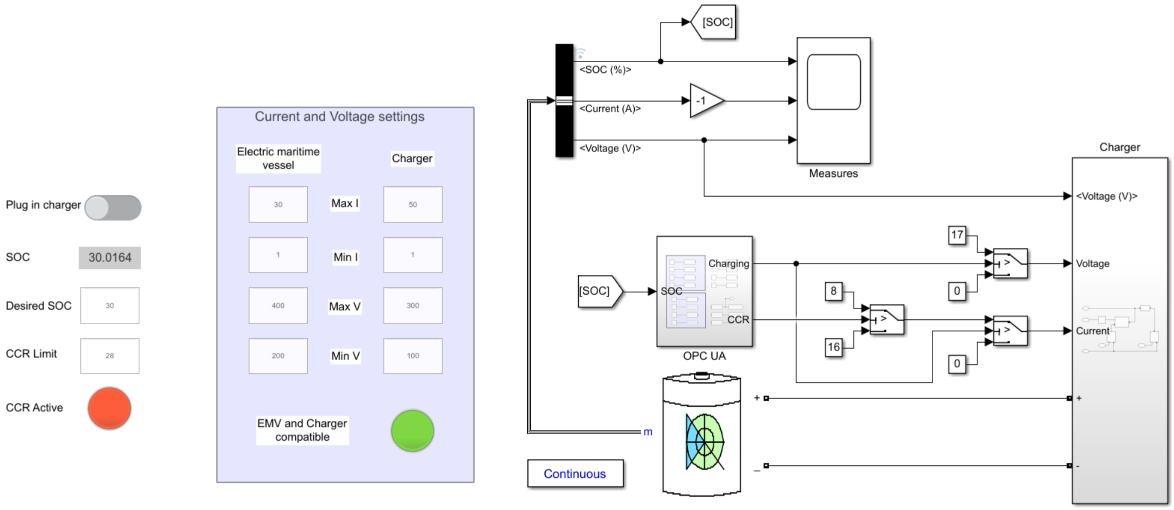


Figure 47: Schematic of the CP circuitry

the software to crash. A manual configuration was attempted by using the help documentation but it did not work. From the previous testing of the serial interface there had been successful transmission of signals with both RS-232 and RS-485. When trying to set up two-way communication between the PLCs however, the signals were blocked and no transmission were possible. To be able to demonstrate some functionality, one-way communication from the EMV PLC to the charger PLC was set up with RS-232 modbus. This type of communication sends the data in forms of either bits or word, thus resulting in not being able to send decimal numbers, only integers. To circumvent this limitation the values are multiplied by 100 before sending and divided by 100 after receiving, giving a number precision of 2 instead of 0.


Plug in charger
SOC 30.0164
Desired SOC 30
CCR Limit 28
CCR Active

Current and Voltage settings

Electric maritime vessel		Charger
30	Max I	50
1	Min I	1
400	Max V	300
200	Min V	100

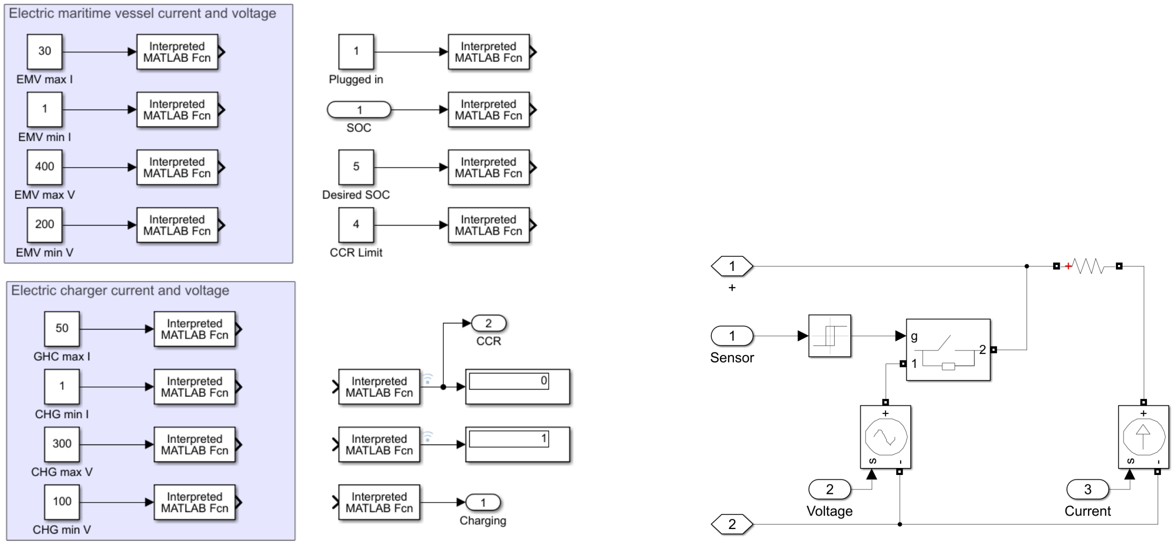
EMV and Charger compatible

Figure 48: Matlab Simulink model with OPC UA communication

A Matlab 2019a Simulink file was made with a simple constant current constant voltage (CCCV) charger and battery as seen in Figure 48. Multiple signals are sent and retrieved from the PLCs with use of Matlab function blocks with OPC UA communication. Separate blocks have been made for each signal, 15 in total. They are all contained in the OPC UA subsystem that can be seen in Figure 49a. The amperage of the constant current source is controlled by both the Charging Current Restriction (CCR) signal and Charging signal from the charger PLC. The Charging signal also controls the voltage for the constant voltage source. The values of the combinations can be found in Table 11 and the charger subsystem can be seen in Figure 49b.

Table 11: PLC signals with corresponding voltage and current in simulation

Charging	**CCR**	**Voltage**	**Current**
False	False	0V	0A
False	True	0V	0A
True	False	17 V	16 A
True	True	17 V	8 A



(a) OPC UA

(b) Charger

Figure 49: The two subsystems in the Matlab model

There are 8 input fields for the maximum and minimum current and voltage for EMV and the charger. These values are written to the corresponding PLCs. The EMV PLC then sends its values to the charger PLC in accordance to the flowchart in Figure 28. The charger PLC compares the values from the EMV with its own and determines if they are compatible. The compatibility is determined by four comparisons as seen in Table 12 which must all be true. A signal is sent back to Matlab were the compatibility is indicated.

Table 12: Compatibility logic of EMV and charger

Comparisons		
EMV min I	$\leq$	CHG max I
EMV max I	$\geq$	CHG min I
EMV min V	$\leq$	CHG min V
EMV max V	$\geq$	CHG max V

There is a display for the battery state of charge (SoC) as well as two additional input fields; desired SoC and CCR Limit. The state of charge and desired SoC is written to the EMV PLC and again these are transferred via RS-232 to the charger PLC so it can regulate the charging. The CCR Limit is written to the charger PLC. The PLC sends a signal back to Matlab to indicate if CCR is active or not. Finally there is a slider switch that simulates that the cable has been plugged in to the inlet. This acts as the Proximity Pilot (PP) in absence of a real plug and inlet.

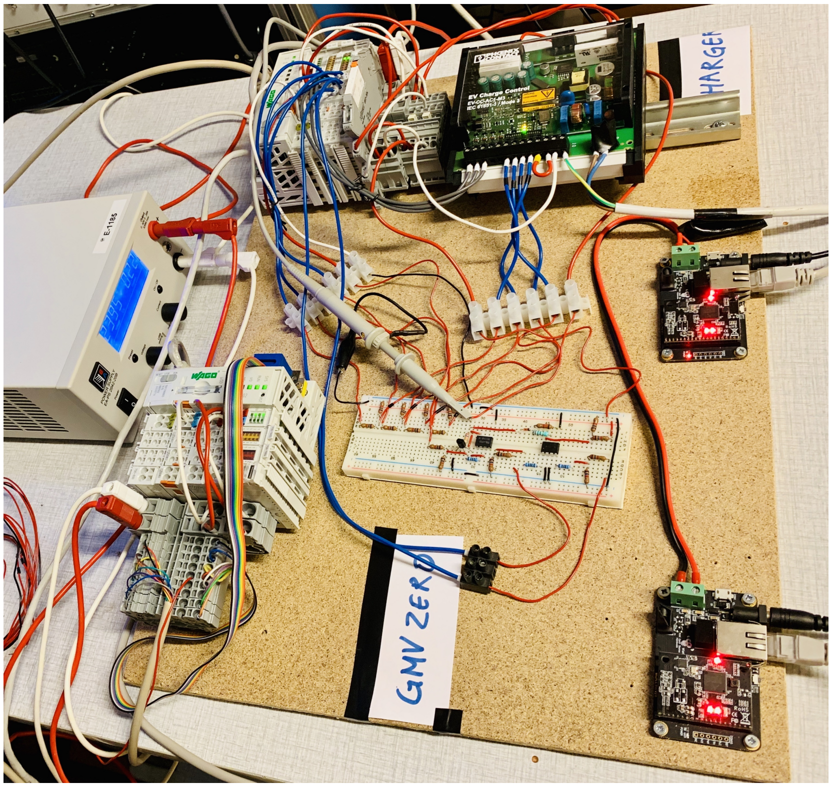


Figure 50: The practical set up

4.9 Charging sequence

All in all, the laboratory test setup runs with Matlab, two PLCs (ChgPLC and EMVPLC) and the EV CC board as seen in Figure 50. The simulation of a successful charging sequence is as follows:

- Matlab: Slide on ”Plug in charger”. Signal sent to ChgPLC
- ChgPLC: Sends signal on DO 5 to connect 2.7 kΩ resistor to CP
- EVCC: CP signal is now 9 V. Sends CON signal to ChgPLC.
- EMVPLC: Sends EMV min/max current/voltage to ChgPLC
- ChgPLC: Compares EMV and Charger min/max current/voltage
- ChgPLC: Sends signal on DO 6 to connect 1.3 kΩ resistor to CP
- EVCC: CP signal is now 6 V.
- ChgPLC: Sends signal on DO 1 to enable charging on EVCC
- EVCC: Sends CHG signal to ChgPLC
- ChgPLC: Sends charging signal to Matlab
- Matlab: Sets voltage to 17 V and current to 16 A on the charger
- Matlab: Continuously sends battery state of charge to EMVPLC
- EMVPLC: Continuously sends battery state of charge and desired SoC to ChgPLC
- ChgPLC: Continuously evaluates the SoC agains desired SoC and CCR limit
- ChgPLC: Sends signal on DO 4 to activate CCR on EVCC. Also sends signal to Matlab
- Matlab: Reduces current from 16 A to 8 A on charger
- ChgPLC: Removes signal from DO 1 and DO 6 to stop charging once SoC $\geq$ desired SoC. Also sends signal to Matlab
- Matlab: Sets voltage to 0 V and current to 0 A on charger

A test with desired SoC set at 30% and CCR limit at 28% yielded to result seen in Figure 51. The current starts at 16 A and the SoC is steadily rising until it reaches 28%. When the current is reduced to 8 A the rate of charge is halved. Once the SoC is 30% the current is set to 0 A and the charging stops. The battery voltage increases with the SoC, but drops a little when the current is reduced and cut off.

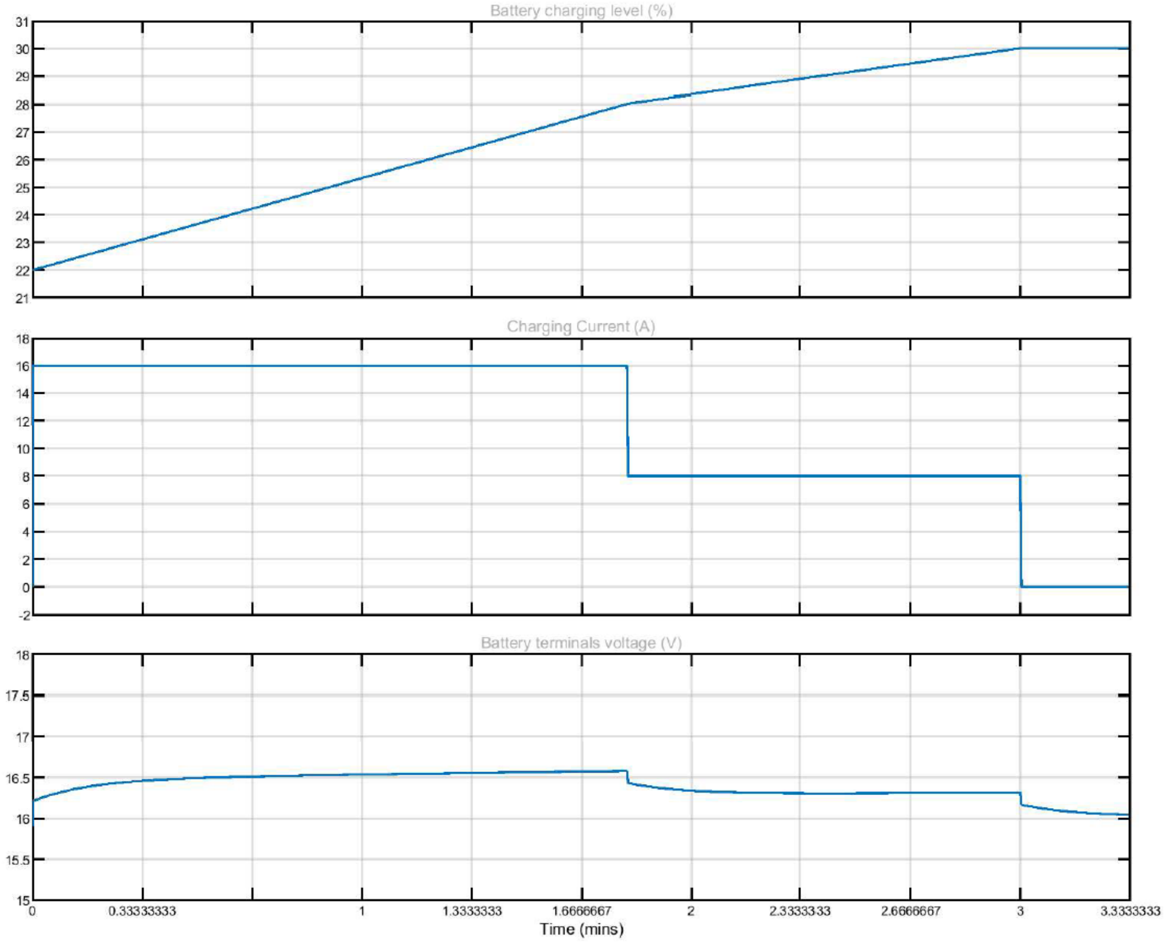


Figure 51: Result of charging test with Matlab, EV CC and PLCs

5 Conclusion

Combined Charging System 2.0 (CCS 2.0) is the best standard for the GMV Zero and other electric maritime vessels (EMVs) in Europe for fast charging. CCS 2.0 uses Power Line Carrier Communication (PLCC) to enable communication between the EMV and the charger. The project has shown that with use of two PLCs it is possible to control the charging sequence with help of an Electric Vehicle Charging Controller (EVCC) board.

The charger PLC will control the EVCC and they will together communicate with the second PLC in the EMV via PLCC over the Control Pilot (CP) line in the CCS 2.0 plug. With this setup it is possible to monitor and control the charging process. It also allows the vessel to offload the heavy voltage transformers to the dock, making the ship lighter and more economical.

5.1 Future work

In this project there have only been Matlab simulation of battery charging. The models have shown that it works fine. Next step is to experiment with real batteries and verify that the simulations are correct.

Some compromises have been made in the project due to technical difficulties. It is possible to get the PLCs to communicate over Ethernet via PLCC, eliminating the need for a serial interface. This can be implemented when the e!COCKPIT software is patched or using other PLCs from a different vendor.

With two-way communication in place and the charging tested on real batteries the system can be implemented in GMV Zero. A user interface must be made and connected to the PLC so the crew can monitor and control the charging process.

References

[1] J.G. Hayes and G.A. Goodarzi. *Electric powertrain: Energy systems, power electronics & drives for hybrid, electric & fuel cell vehicles*. wiley, 2019, pp. 1–530. ISBN: 9781119063681.

[2] *Norway is leading the way for a transition to zero emission in transport*. 2018. URL: https://elbil.no/english/norwegian-ev-policy/ (visited on 08/12/2018).

[3] M. Brenna et al. 'The strategies for the diffusion of EVs: Focus on Norway and Italy'. In: *2017 Twelfth International Conference on Ecological Vehicles and Renewable Energies (EVER)*. 2017, pp. 1–5. DOI: 10.1109/EVER.2017.7935891.

[4] *Fully battery electric driven car ferry*. 2014. URL: http://www.fjellstrand.no/flyers/flyer_1696.pdf (visited on 11/06/2019).

[5] *CBnr. 138 – GMV Zero*. 2016. URL: http://www.gmv.no/portfolio-item/bnr-138-gmv-zero/ (visited on 06/02/2019).

[6] *Klart for bygging av verdens første el-røkterbåt til oppdrettsnæringen*. 2016. URL: https://kupa.no/klart-bygging-verdens-forste-el-rokterbat-oppdrettsnaeringen/ (visited on 06/02/2019).

[7] *Oppdrettsbransjens første nullutslippsinnovasjon*. 2018. URL: https://www.wago.com/no/martimt/gmvzero (visited on 06/02/2019).

[8] *Plug In Electric Vehicles in Smart Grids: Energy Management*. eng. 2015th ed. Power Systems. Singapore: Springer Singapore, 2015. ISBN: 9789812873019.

[9] Z. Ning and Z. Kuzhu. 'Research on Prevention and Control Technologies of Harbor Pollution'. In: *2009 International Conference on Energy and Environment Technology*. Vol. 2. 2009, pp. 713–716. DOI: 10.1109/ICEET.2009.410.

[10] Renilde Becqué, Freda Fung and Zhixi Zhu. *Incentive schemes for promoting green shipping*. Tech. rep. The Natural Resources Defense Council, 2018.

[11] C. P. Leung and K. W. E. Cheng. 'Zero emission solar-powered boat development'. In: *2017 7th International Conference on Power Electronics Systems and Applications - Smart Mobility, Power Transfer Security (PESA)*. 2017, pp. 1–6. DOI: 10.1109/PESA.2017.8277736.

[12] *Green Shipping Programme*. 2019. URL: https://www.dnvgl.com/maritime/green-shipping-programme/index.html (visited on 11/06/2019).

[13] F. Balsamo et al. 'Main issues with the design of batteries to power full electric water busses'. In: *2016 AEIT International Annual Conference (AEIT)*. 2016, pp. 1–6. DOI: 10.23919/AEIT.2016.7892784.

[14] Hiroyasu Kifune, Masaya Satou and Tsuyoshi Oode. 'Study on Battery System Design for Battery Ships Conforming to CHAdeMO'. In: *Journal of the JIME* 51.6 (2016), pp. 134–141.

[15] C. S. Postiglione et al. ‘Propulsion system for an all electric passenger boat employing permanent magnet synchronous motors and modern power electronics’. In: *2012 Electrical Systems for Aircraft, Railway and Ship Propulsion*. 2012, pp. 1–6. DOI: 10.1109/ESARS.2012.6387441.

[16] T. Takamasa et al. ‘Quick charging plug-in electric boat “RAICHO-I”’. In: *2011 IEEE Electric Ship Technologies Symposium*. 2011, pp. 9–11. DOI: 10.1109/ESTS.2011.5770829.

[17] G. S. Spagnolo, D. Papalilo and A. Martocchia. ‘Eco friendly electric propulsion boat’. In: *2011 10th International Conference on Environment and Electrical Engineering*. 2011, pp. 1–4. DOI: 10.1109/EEEIC.2011.5874699.

[18] K. W. E. Cheng, X. D. Xue and K. H. Chan. ‘Zero emission electric vessel development’. In: *2015 6th International Conference on Power Electronics Systems and Applications (PESA)*. 2015, pp. 1–5. DOI: 10.1109/PESA.2015.7398965.

[19] *New type of Plug-in Electric boats ”RAICHO”s*. 2010. URL: http://www2.kaiyodai.ac.jp/~takamasa/kaiyodai-ees-project/kaiyodai-ees-projectE21-3.html (visited on 06/02/2019).

[20] S. S. Nag et al. ‘An isolated bipolar DC-DC converter for energy storage integration in marine vessels’. In: *IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society*. 2017, pp. 6765–6770. DOI: 10.1109/IECON.2017.8217182.

[21] A. Arancibia and K. Strunz. ‘Modeling of an electric vehicle charging station for fast DC charging’. In: *2012 IEEE International Electric Vehicle Conference*. Mar. 2012, pp. 1–6. DOI: 10.1109/IEVC.2012.6183232.

[22] M. Zhang et al. ‘Research on static voltage stability based on EV charging station load modeling’. In: *2011 International Conference on Advanced Power System Automation and Protection*. Vol. 2. Oct. 2011, pp. 1094–1099. DOI: 10.1109/APAP.2011.6180969.

[23] *Constant Voltage, Constant Current Battery Charging*. 2016. URL: http://power-topics.blogspot.com/2016/05/constant-voltage-constant-current.html (visited on 11/06/2019).

[24] C. Dericioglu et al. ‘A review of charging technologies for commercial electric vehicles’. In: *International Journal of Advances on Automotive and Technology* 2 (Jan. 2018), pp. 61–70. DOI: 10.15659/ijaat.18.01.892.

[25] *Technologies and Applications for Smart Charging of Electric and Plug-in Hybrid Vehicles*. eng. Cham, 2017.

[26] *Plug-In Around the EV World*. URL: http://www.ev-institute.com/images/media/Plug_World_map_v4.pdf (visited on 03/06/2019).

[27] *Sammenlikn pris, rekkevidde og garanti på elbiler du kan kjøpe i dag*. 2019. URL: https://elbil.no/om-elbil/elbiler-idag/#all (visited on 05/06/2019).

[28] Clemente Capasso et al. ‘Charging Architectures Integrated with Distributed Energy Resources for Sustainable Mobility’. In: *Energy Procedia* 105 (May 2017), pp. 2317–2322. DOI: 10.1016/j.egypro.2017.03.666.

[29] NEK IEC 61851:1-2017. *Electrical vehicle conductive charging system*. Standard. 3 rue de Varambé, CH-1211 Geneva 20, Switzerland: Norsk Elektroniske Komite, 2017.

[30] G. R. C. Mouli et al. 'Implementation of dynamic charging and V2G using Chademo and CCS/Combo DC charging standard'. In: *2016 IEEE Transportation Electrification Conference and Expo (ITEC)*. 2016, pp. 1–6. DOI: 10.1109/ITEC.2016.7520271.

[31] M. C. Falvo et al. 'EV charging stations and modes: International standards'. In: *2014 International Symposium on Power Electronics, Electrical Drives, Automation and Motion*. June 2014, pp. 1134–1139. DOI: 10.1109/SPEEDAM.2014.6872107.

[32] Muhammad Aziz. 'Advanced Charging System for Plug-in Hybrid Electric Vehicles and Battery Electric Vehicles'. In: *Hybrid Electric Vehicles*. Ed. by Teresa Donateo. Rijeka: IntechOpen, 2017. Chap. 3. DOI: 10.5772/intechopen.68287. URL: https://doi.org/10.5772/intechopen.68287.

[33] *SAE J1772*. 2019. URL: https://en.wikipedia.org/wiki/SAE_J1772 (visited on 04/06/2019).

[34] Deepak Ravi et al. 'Bidirectional dc to dc Converters: An Overview of Various Topologies, Switching Schemes and Control Techniques'. In: *International Journal of Engineering and Technology* 7 (Sept. 2018), pp. 360–365. DOI: 10.14419/ijet.v7i4.5.20107.

[35] Euzeli dos Santos. *Advanced Power Electronics Converters : PWM Converters Processing AC Voltages*. eng. Hoboken, 2014.

[36] R. H. G. Tan and L. Y. H. Hoo. 'DC-DC converter modeling and simulation using state space approach'. In: *2015 IEEE Conference on Energy Conversion (CENCON)*. Oct. 2015, pp. 42–47. DOI: 10.1109/CENCON.2015.7409511.

[37] T. Freire, D. M. Sousa and P. J. C. Branco. 'Modeling the electric chain of an electric boat'. In: *2011 IEEE EUROCON - International Conference on Computer as a Tool*. Apr. 2011, pp. 1–4. DOI: 10.1109/EUROCON.2011.5929400.

[38] J. Rojas et al. 'Partial power DC-DC converter for electric vehicle fast charging stations'. In: *IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society*. Oct. 2017, pp. 5274–5279. DOI: 10.1109/IECON.2017.8216913.

[39] M. Saleh et al. 'Design and implementation of CCNY DC microgrid testbed'. In: *2016 IEEE Industry Applications Society Annual Meeting*. Oct. 2016, pp. 1–7. DOI: 10.1109/IAS.2016.7731870.

[40] *AC charging controller - EV-CC-AC1-M3-CBC-SER-HS - 1622452*. 2019. URL: https://www.phoenixcontact.com/online/portal/us?uri=pxc-oc-itemdetail:pid=1622452&library=usen&tab=1 (visited on 04/06/2019).

[41] *History of the PLC*. URL: https://library.automationdirect.com/history-of-the-plc/ (visited on 02/06/2019).

[42] *PLC: Industrial Applications of Programmable Logic Controller*. 2017. URL: https://www.mobileautomation.com.au/plc-industrial-application/ (visited on 04/06/2019).

[43] Mike Bacidore. *Programming a PLC vs. industrial PC: which is best?* 2017. URL: https://www.controldesign.com/articles/2017/programming-a-plc-vs-industrial-pc-which-is-best/ (visited on 04/06/2019).

[44] Phillip Lipson and Geert van der Zalm. *Inside Machines: PC versus PLC: Comparing control options*. 2011. URL: https://www.controleng.com/articles/inside-machines-pc-versus-plc-comparing-control-options/ (visited on 04/06/2019).

[45] Clyde Herrick. *Basic Electronics Math*. Elsevier Science, 1996. ISBN: 075069727X.

[46] *WisPLC Pro Power Line Development Board*. 2019. URL: https://uk.pi-supply.com/products/wisplc-pro-power-line-development-board-plc-module-with-power-line-twisted-pair-ethernet-interface-500mbps-and-network-adapter-includes-lx200v30 (visited on 11/06/2019).

[47] T. Huck et al. 'Tutorial about the implementation of a vehicular high speed communication system'. In: *International Symposium on Power Line Communications and Its Applications, 2005*. Apr. 2005, pp. 162–166. DOI: 10.1109/ISPLC.2005.1430488.

[48] A. Pittolo et al. 'In-Vehicle Power Line Communication: Differences and Similarities Among the In-Car and the In-Ship Scenarios'. In: *IEEE Vehicular Technology Magazine* 11.2 (June 2016), pp. 43–51. ISSN: 1556-6072. DOI: 10.1109/MVT.2015.2480098.

[49] S. Barmada et al. 'Power Line Communication in a full electric vehicle: Measurements, modelling and analysis'. In: *ISPLC2010*. Mar. 2010, pp. 331–336. DOI: 10.1109/ISPLC.2010.5479920.

[50] Y. Zhang et al. 'An implementation of an in-vehicle power line communication system'. In: *2017 IEEE 6th Global Conference on Consumer Electronics (GCCE)*. Oct. 2017, pp. 1–2. DOI: 10.1109/GCCE.2017.8229422.

[51] *CCS Communication*. 2019. URL: https://www.charinev.org/faq/ (visited on 22/04/2019).

[52] A. M. Tonello and A. Pittolo. 'Considerations on narrowband and broadband power line communication for smart grids'. In: *2015 IEEE International Conference on Smart Grid Communications (SmartGridComm)*. Nov. 2015, pp. 13–18. DOI: 10.1109/SmartGridComm.2015.7436269.

[53] ISO 15118-3:2015. *Road vehicles - Vehicle to grid Communication interface - Part 3: Physical and data link requirements*. Standard. Avenue Marnix 17, B-1000 Brussels: European Committee for Standardization, 2015.

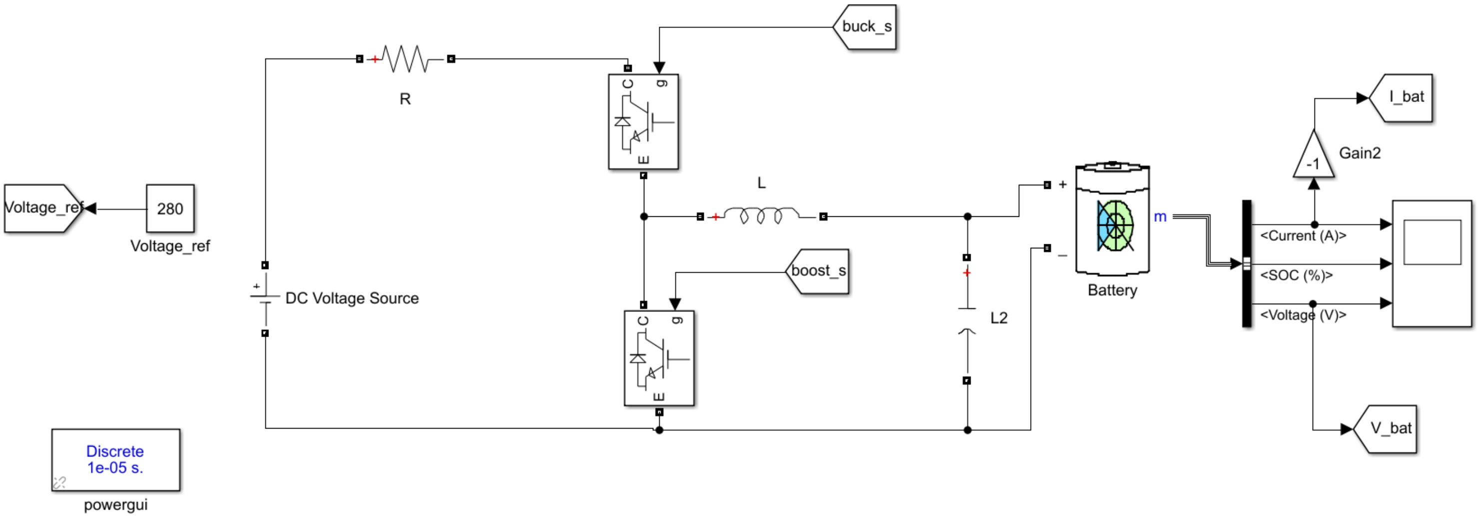
[54] *What is OPC?* 2019. URL: https://opcfoundation.org/about/what-is-opc/ (visited on 05/06/2019).

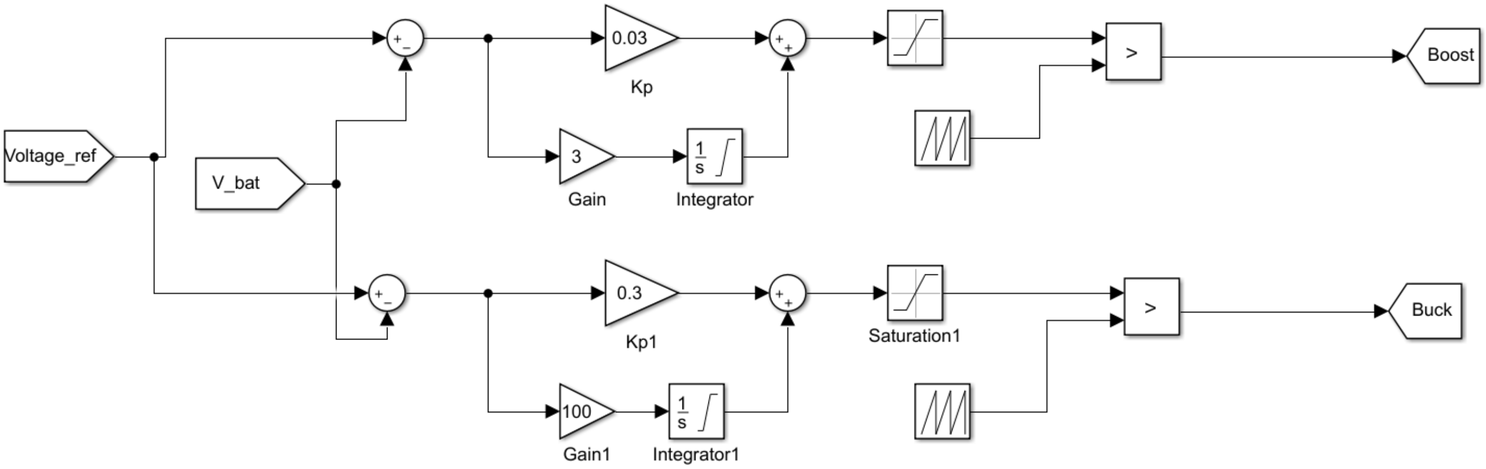
[55] *Unified Architecture - OPC Foundation*. 2019. URL: https://opcfoundation.org/about/opc-technologies/opc-ua/ (visited on 05/06/2019).

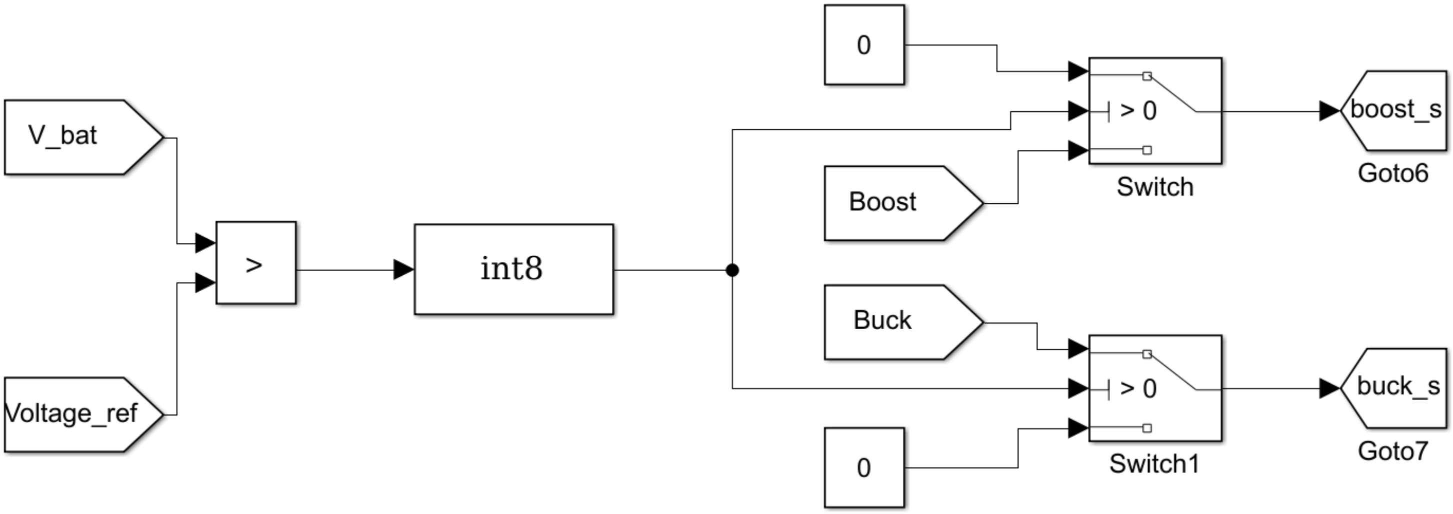
[56] *Unified Architecture - MATLAB & Simulink*. 2019. URL: https://se.mathworks.com/help/opc/unified-architecture.html (visited on 05/06/2019).

[57] *Digitalization with TIA Portal: Virtual Commissioning with SIMATIC and Simulink*. 2018. URL: https://support.industry.siemens.com/cs/document/109749187/digitalization-with-tia-portal%3A-virtual-commissioning-with-simatic-and-simulink?dti=0&lc=en-WW (visited on 03/06/2019).

A Bidirectional DC-DC charging Matlab model


buck_s
R
I_bat
Gain2
-1
Voltage_ref
280
Voltage_ref
L
m
<Current (A)>
<SOC (%)>
<Voltage (V)>
Battery
DC Voltage Source
boost_s
L2
V_bat
Discrete
1e-05 s.
powergui


0.03
Kp
>
Boost
Voltage_ref
V_bat
3
Gain
1/s
Integrator
0.3
Kp1
>
Buck
Saturation1
100
Gain1
1/s
Integrator1


0
> 0
Switch
boost_s
Goto6
V_bat
Boost
>
int8
Buck
> 0
Switch1
buck_s
Goto7
Voltage_ref
0

B Wago PLC code

Project Documentation

File:	PLC with OPC double.ecp
Date:	6/9/2019
Profile:	e!COCKPIT

Table of Contents

1 Application: Application

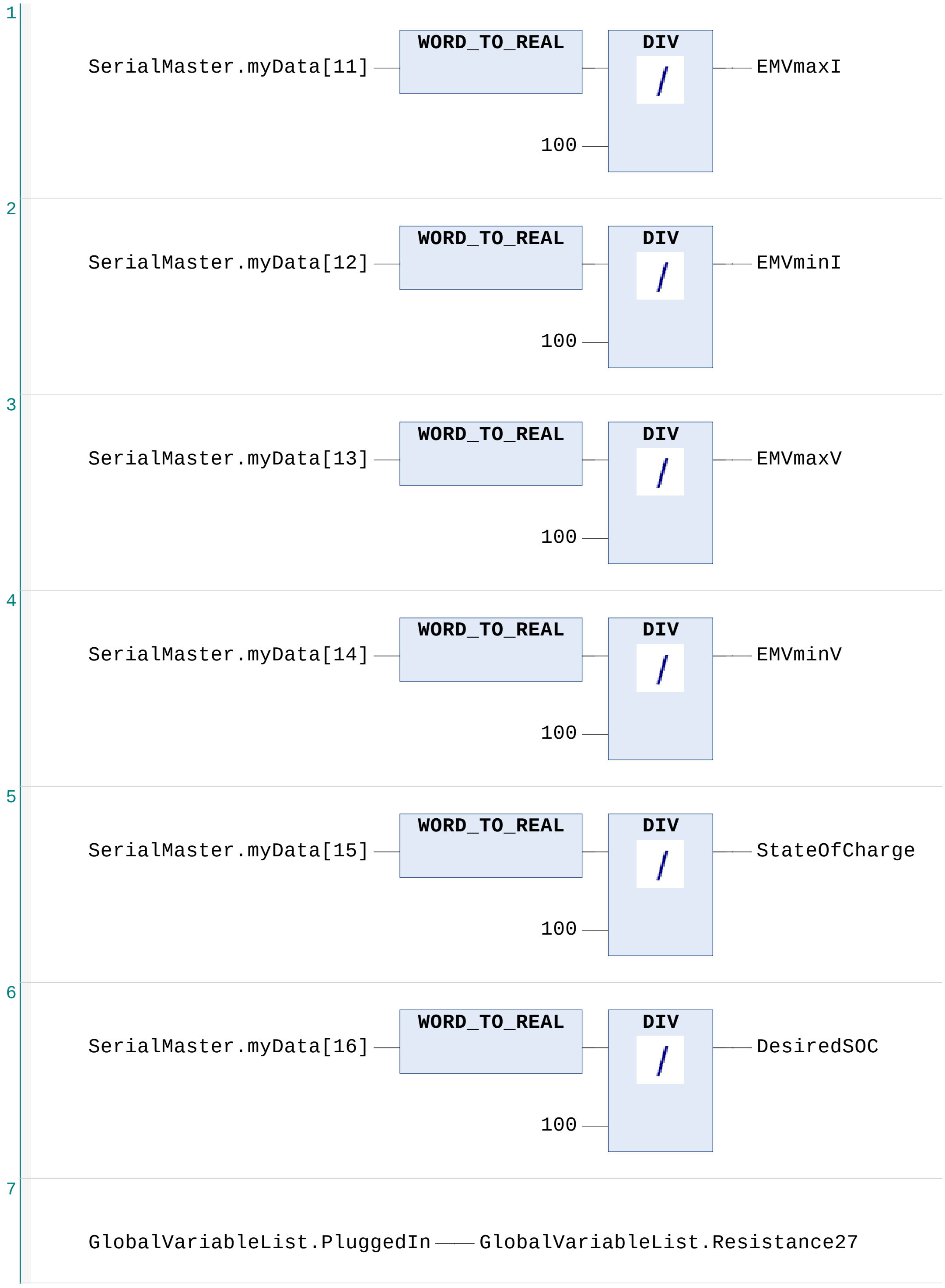
1.1 Global Variable List: GlobalVariableList

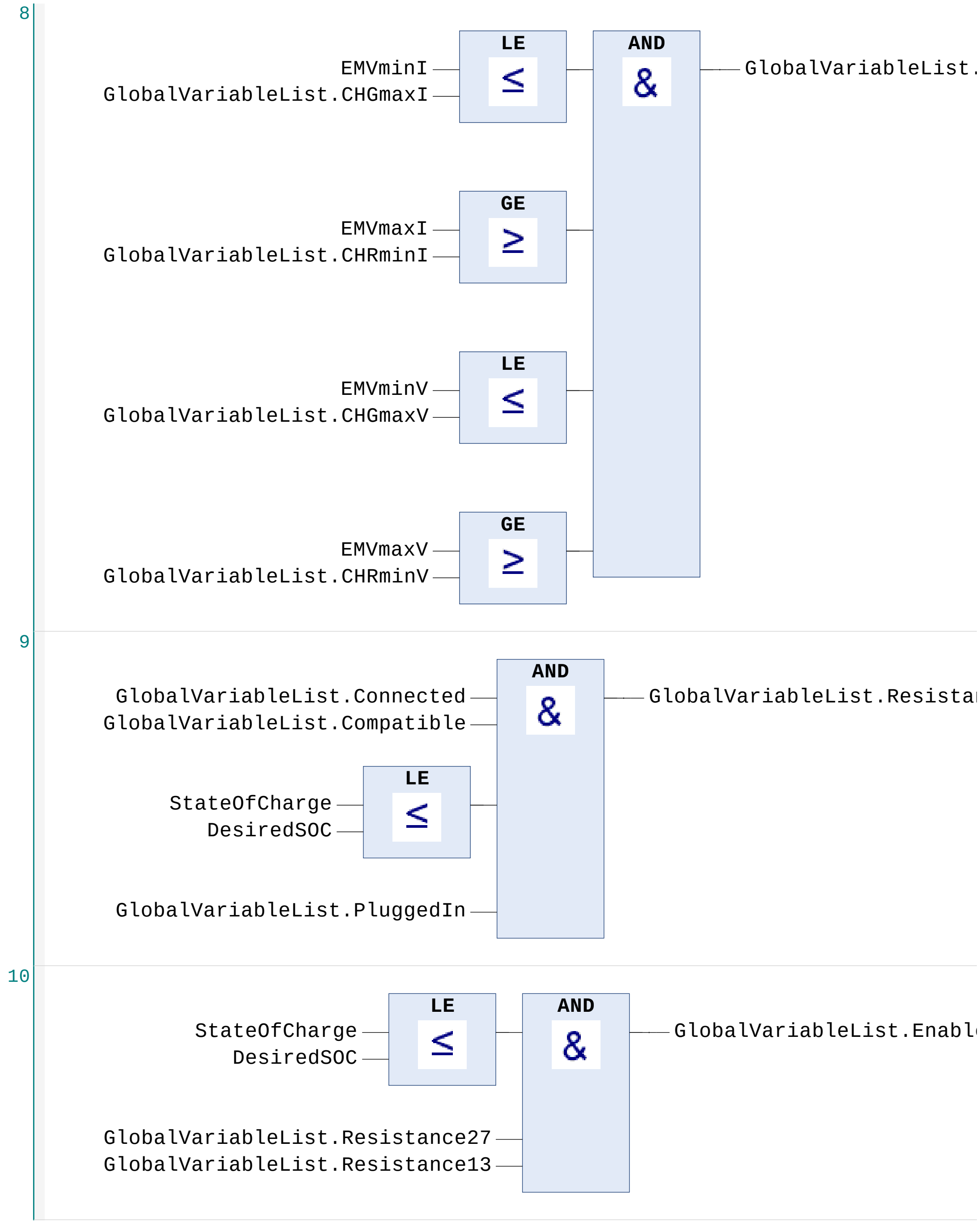
```
{attribute 'qualified_only'}
VAR_GLOBAL
    Error :  BOOL ;
    Charging :  BOOL ;
    Connected :  BOOL ;
    Enabled :  BOOL ;
    Status :  BOOL ;
    ManualLocking :  BOOL ;
    ChargingCurrentLimit :  BOOL ;
    StateOfCharge :  REAL ;
    PluggedIn :  BOOL ;
    Resistance27 :  BOOL ;
    Resistance13 :  BOOL ;
    EMVmaxI :  REAL ;
    EMVmaxV :  REAL ;
    EMVminI :  REAL ;
    EMVminV :  REAL ;
    CHGmaxI :  REAL ;
    CHGmaxV :  REAL ;
    CHRminI :  REAL ;
    CHRminV :  REAL ;
    Compatible :  BOOL ;
    DesiredSOC :  REAL ;
    CCRLimit :  REAL ;
END_VAR

```

1.2 POU: ChargerLogic

```
PROGRAM  ChargerLogic
VAR
    EMVmaxI         :  REAL ;
    EMVminI         :  REAL ;
    EMVmaxV         :  REAL ;
    EMVminV         :  REAL ;
    StateOfCharge   :  REAL ;
    DesiredSOC      :  REAL ;
END_VAR

```

1.2 POU: ChargerLogic

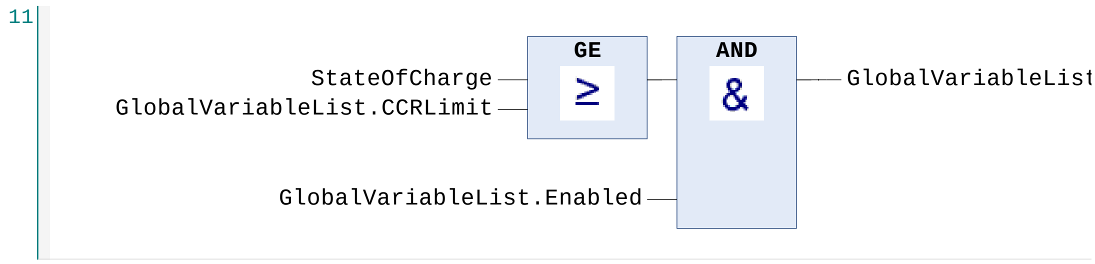



8
LE
≤
AND
&
EMVminI
GlobalVariableList.CHGmaxI
GlobalVariableList.
GE
≥
EMVmaxI
GlobalVariableList.CHRminI
LE
≤
EMVminV
GlobalVariableList.CHGmaxV
GE
≥
EMVmaxV
GlobalVariableList.CHRminV
9
AND
&
GlobalVariableList.Connected
GlobalVariableList.Compatible
GlobalVariableList.Resista
LE
≤
StateOfCharge
DesiredSOC
GlobalVariableList.PluggedIn
10
LE
≤
AND
&
StateOfCharge
DesiredSOC
GlobalVariableList.Enabl
GlobalVariableList.Resistance27
GlobalVariableList.Resistance13

Compatible

nce13

ed


11
GE
≥
AND
&
StateOfCharge
GlobalVariableList.CCRLimit
GlobalVariableList.Enabled
GlobalVariableList

```
.ChargingCurrentLimit
```

1.3 POU: InputMapping

```
PROGRAM InputMapping

```

```
1

    ERR —— GlobalVariableList.Error

2

    CHG —— GlobalVariableList.Charging

3

    CON —— GlobalVariableList.Connected
```

1.4 POU: OutputMapping

```
PROGRAM  OutputMapping
VAR
END_VAR

```

```
1
    GlobalVariableList.Enabled——EN
2
    GlobalVariableList.Status——XR
3
    GlobalVariableList.ManualLocking——ML
4
    GlobalVariableList.ChargingCurrentLimit——CCR
5
    GlobalVariableList.Resistance27—○—OHM27
6
    GlobalVariableList.Resistance13—○—OHM13
```

1.5 POU: PLC_PRG

```
PROGRAM  PLC_PRG
VAR
END_VAR

```

```
InputMapping ( ) ;
SerialMaster ( ) ;
ChargerLogic ( ) ;
//SerialSlave();
OutputMapping ( ) ;

```

1.6 POU: SerialMaster

```
PROGRAM  SerialMaster
VAR
    FbMbMasterSerial_01      :  FbMbMasterSerial ;
    xConnect                 :  BOOL  :=  TRUE ;
    utQuery                  :  typMbQuery ;
    xTrigger                 :  BOOL ;
    uTResponse               :  typMbResponse ;
    xError                   :  BOOL ;
    oStatus                  :  WagoAppPlcModbus . WagoSysErrorBase . FbResult ;
    xIsConnected             :  BOOL ;
    wDelta                   :  WORD ;
    T1                       :  TON ;
    xMyError                 :  BOOL ;
END_VAR
VAR_OUTPUT
    myData                   :  ARRAY  [ 0 . . 124 ]  OF  WORD ;
END_VAR

```

```
utQuery . bFunctionCode := 23 ;
utQuery . uiReadAddress := 0 ;
utQuery . uiReadQuantity := 50 ;
utQuery . uiWriteAddress := 1 ;
utQuery . uiWriteQuantity := 4 ;
utQuery . bUnitId := 2 ;
utQuery . awWriteData [ 0 ] := utQuery . awWriteData [ 0 ] + 1 ;

FbMbMasterSerial_01 (
    xConnect        :=  xConnect ,
    I_Port          :=  COM1 ,
    udiBaudrate     :=  9600 ,
    usiDataBits     :=  8 ,
    eParity         :=  1 ,          //ettyparity.None ,
    eStopBits       :=  3 ,          //ettystopbits.One ,
    eHandshake      :=  0 ,          //ettyhandshake.None ,
    ePhysical       :=  1 ,
    xIsConnected    =>  xIsConnected ,
```

```
        xError          =>  xError ,
        oStatus         =>  oStatus ,
        eFrameType      :=  eMbFrametype . RTU ,
        tTimeOut        :=  T#200MS ,
        utQuery         :=  utQuery ,
        xTrigger        :=  xTrigger ,
        utResponse      :=  utResponse ) ;

    myData := utResponse . awData ;
    myData [ 0 ] ;
    T1 ( IN  :=  NOT  xTrigger ,  PT  :=  T#200MS ) ;
    IF  T1 . Q  THEN
        xTrigger  :=  TRUE ;
    END_IF


```

1.7 POU: SerialSlave

```
    PROGRAM  SerialSlave
    VAR
        FbMbSimpleServerSerial_01   :  FbMbSimpleServerSerial ;
        xConnect                    :  BOOL  :=  TRUE ;
        axDiscreteInputs            :  ARRAY [ 0 .. 100 ]  OF  BOOL ;        //Slave outputs (MasterInputs)
        axCoils                     :  ARRAY [ 0 .. 100 ]  OF  BOOL ;        //Slave Inputs (Master Output)
        awInputRegisters            :  ARRAY [ 0 .. 100 ]  OF  WORD ;        //Slave outputs (MasterInputs)
        awHoldingRegisters          :  ARRAY [ 0 .. 100 ]  OF  WORD ;        //Slave Inputs (Master outputs)
        xIsConnected                :  BOOL ;
        xError                      :  BOOL ;
        oStatus                     :  WagoAppPlcModbus . WagoSysErrorBase . FbResult ;
        oMbAccessInfo               :  FbMbAccessInfo ;
    END_VAR

```

```
    FbMbSimpleServerSerial_01 (
        xConnect        :=  xConnect ,
        I_Port          :=  COM1 ,
        udiBaudrate     :=  9600 ,
        usiDataBits     :=  8 ,
        eParity         :=  1 ,
        eStopBits       :=  3 ,
        eHandshake      :=  0 ,
        ePhysical       :=  1 ,  //WagoTypesCom.eTTYphysicallayer.RS485_HalfDuplex,
        eFrameType      :=  eMbFrameType . RTU ,
        xIsConnected    =>  xIsConnected ,
        xError          =>  xError ,
        oStatus         =>  oStatus ,
        bUnitId         :=  1 ,
        axDiscreteInputs    :=  axDiscreteInputs ,
```

```
        axCoils             :=  axCoils ,
        awInputRegisters    :=  awInputRegisters ,
        awHoldingRegisters  :=  awHoldingRegisters ,
        oMbAccessInfo       =>  oMbAccessInfo ) ;

    awHoldingRegisters [ 1 ] ;         // (* First Write register *)
    awHoldingRegisters [ 10 ]  :=  awHoldingRegisters [ 10 ] - 1 ;        //(* First
    Read register *)

```

1.8 POU: TcpModbusMaster

```
    PROGRAM  TcpModbusMaster
    VAR
        myTcpMaster     :  FbMbMasterTcp     :=  (   xConnect     :=  TRUE ,
                                                     sHost       :=  '192.168.1.18' ,
                                                     wPort       :=  502 ,

                                                     utKeepAlive :=  (   xEnable
             :=  TRUE ,
                                                                         tMaxIdleTime
        :=  T#5S ,
                                                                         tInterval
           :=  T#2S ,
                                                                         udiProbes
           :=  5
                                                                     ) ,

                                                     eFrameType   :=  eMbFrameType .
    ETHERNET ,
                                                     tTimeOut     :=  T#30MS
                                                 ) ;

        utQuery         :  typMbQuery    :=  (   bUnitId          :=  1 ,
                                                 bFunctionCode    :=  23 ,
                                                 uiReadAddress    :=  1 ,
                                                 uiReadQuantity   :=  10 ,
                                                 uiWriteAddress   :=  1 ,
                                                 uiWriteQuantity  :=  10 ,
                                                 awWriteData      :=  [ 124 ( 0 ) ]
                                             ) ;

        xTxTrigger      :  BOOL ;

        utResponse      :  typMbResponse ;

        tonDelay        :  TON  :=  ( PT  :=  T#20MS ) ;

    //        myData                    : ARRAY[0..124] OF WORD;
    //        xTrigger              : BOOL;
    //        T1: TON;

    END_VAR

```

```
tonDelay (  IN  :=  ( NOT  tonDelay . Q )  AND  ( NOT  xTxTrigger ) ) ;
xTxTrigger  S=  tonDelay . Q ;

myTcpMaster (   utQuery     :=  utQuery ,
                xTrigger    :=  xTxTrigger ,
                utResponse  :=  utResponse
            ) ;

//myData        := myTcpMaster.utResponse.awData;
//myData[0];
//T1(IN := NOT xTrigger, PT := T#200MS);
//IF T1.Q THEN
//        xTrigger := TRUE;
//END_IF

```

1.9 POU: TcpModbusSlave

```
PROGRAM  TcpModbusSlave
VAR
    mySimpleTcpServer   :   FbMbSimpleServerTcp  :=  (   xOpen        :=  TRUE
,
                                                         wPort        :=  502 ,
                                                         utKeepAlive  :=  (
xEnable         :=  TRUE ,

tMaxIdleTime    :=  T#5S ,

tInterval       :=  T#2S ,

udiProbes       :=  5
                                                                          ) ,
                                                         bUnitId      :=  1
                                                     ) ;
    myDiscreteInputs    :   ARRAY [ 0 .. 20 ]  OF  BOOL ;
    myCoils             :   ARRAY [ 0 .. 20 ]  OF  BOOL ;
    myInputRegisters    :   ARRAY [ 100 .. 200 ]  OF  WORD ;
    myHoldingRegisters  :   ARRAY [ 0 .. 20 ]  OF  WORD ;
END_VAR

```

```
mySimpleTcpServer   (   axDiscreteInputs    :=  myDiscreteInputs ,
                        axCoils             :=  myCoils ,
                        awInputRegisters    :=  myInputRegisters ,
                        awHoldingRegisters  :=  myHoldingRegisters
                    ) ;

```

1.10 Symbol Configuration: Symbols

2 Application: Application

2.1 Global Variable List: GlobalVariableList

```
{attribute 'qualified_only'}
VAR_GLOBAL
    Error :  BOOL ;
    Charging :  BOOL ;
    Connected :  BOOL ;
    Enabled :  BOOL ;
    Status :  BOOL ;
    ManualLocking :  BOOL ;
    ChargingCurrentLimit :  BOOL ;
    StateOfCharge :  REAL ;
    PluggedIn :  BOOL ;
    Resistance27 :  BOOL ;
    Resistance13 :  BOOL ;
    EMVmaxI :  REAL ;
    EMVmaxV :  REAL ;
    EMVminI :  REAL ;
    EMVminV :  REAL ;
    CHGmaxI :  REAL ;
    CHGmaxV :  REAL ;
    CHRminI :  REAL ;
    CHRminV :  REAL ;
    Compatible :  BOOL ;
    DesiredSOC :  REAL ;
    CCRLimit :  REAL ;
END_VAR

```

2.2 POU: PLC_PRG

```
PROGRAM  PLC_PRG
VAR
END_VAR

```

```
//SerialMaster();
VesselLogic ( ) ;
SerialSlave ( ) ;


```

2.3 POU: SerialMaster

```
PROGRAM  SerialMaster
VAR
    FbMbMasterSerial_01      :  FbMbMasterSerial ;
    xConnect                 :  BOOL  :=  TRUE ;
    utQuery                  :  typMbQuery ;
    xTrigger                 :  BOOL ;
    uTResponse               :  typMbResponse ;
    xError                   :  BOOL ;
    oStatus                  :  WagoAppPlcModbus . WagoSysErrorBase . FbResult ;
    xIsConnected             :  BOOL ;
    wDelta                   :  WORD ;
    T1                       :  TON ;
    xMyError                 :  BOOL ;
    myData                   :  ARRAY  [ 0 .. 124 ]  OF  WORD ;

END_VAR

```

```
utQuery . bFunctionCode := 23 ;
utQuery . uiReadAddress := 0 ;
utQuery . uiReadQuantity := 50 ;
utQuery . uiWriteAddress := 1 ;
utQuery . uiWriteQuantity := 4 ;
utQuery . bUnitId := 1 ;
utQuery . awWriteData [ 0 ] := utQuery . awWriteData [ 0 ] + 1 ;

FbMbMasterSerial_01 (
    xConnect         :=  xConnect ,
    I_Port           :=  COM1 ,
    udiBaudrate      :=  9600 ,
    usiDataBits      :=  8 ,
    eParity          :=  1 ,          //ettyparity.None ,
    eStopBits        :=  3 ,          //ettystopbits.One ,
    eHandshake       :=  0 ,          //ettyhandshake.None ,
    ePhysical        :=  1 ,
    xIsConnected     =>  xIsConnected ,
    xError           =>  xError ,
    oStatus          =>  oStatus ,
    eFrameType       :=  eMbFrametype . RTU ,
    tTimeOut         :=  T#200MS ,
    utQuery          :=  utQuery ,
    xTrigger         :=  xTrigger ,
    utResponse       :=  utResponse ) ;

myData := utResponse . awData ;
myData [ 0 ] ;
T1 ( IN  :=  NOT  xTrigger ,  PT  :=  T#200MS ) ;
IF  T1 . Q  THEN
    xTrigger  :=  TRUE ;
END_IF


```

2.4 POU: SerialSlave

```
PROGRAM  SerialSlave
VAR
    FbMbSimpleServerSerial_01   :  FbMbSimpleServerSerial ;
    xConnect                    :  BOOL  :=  TRUE ;
    axDiscreteInputs            :  ARRAY [ 0 .. 100 ]  OF  BOOL ;        //Slave outputs (MasterInputs)
    axCoils                     :  ARRAY [ 0 .. 100 ]  OF  BOOL ;        //Slave Inputs (Master Output)
    awInputRegisters            :  ARRAY [ 0 .. 100 ]  OF  WORD ;        //Slave outputs (MasterInputs)

    xIsConnected                :  BOOL ;
    xError                      :  BOOL ;
    oStatus                     :  WagoAppPlcModbus . WagoSysErrorBase . FbResult ;
    oMbAccessInfo               :  FbMbAccessInfo ;
END_VAR
VAR_INPUT
    awHoldingRegisters          :  ARRAY [ 0 .. 100 ]  OF  WORD ;        //Slave Inputs (Master outputs)
END_VAR

```

```
FbMbSimpleServerSerial_01 (
    xConnect        :=  xConnect ,
    I_Port          :=  COM1 ,
    udiBaudrate     :=  9600 ,
    usiDataBits     :=  8 ,
    eParity         :=  1 ,
    eStopBits       :=  3 ,
    eHandshake      :=  0 ,
    ePhysical       :=  1 , //WagoTypesCom.eTTYphysicallayer.RS485_HalfDuplex,
    eFrameType      :=  eMbFrameType . RTU ,
    xIsConnected    =>  xIsConnected ,
    xError          =>  xError ,
    oStatus         =>  oStatus ,
    bUnitId         :=  2 ,
    axDiscreteInputs    :=  axDiscreteInputs ,
    axCoils             :=  axCoils ,
    awInputRegisters    :=  awInputRegisters ,
    awHoldingRegisters  :=  awHoldingRegisters ,
    oMbAccessInfo       =>  oMbAccessInfo ) ;

awHoldingRegisters [ 1 ] ;        // (* First Write register *)
awHoldingRegisters [ 10 ]  :=  awHoldingRegisters [ 10 ] - 1 ;        //(* First Read register *)

```

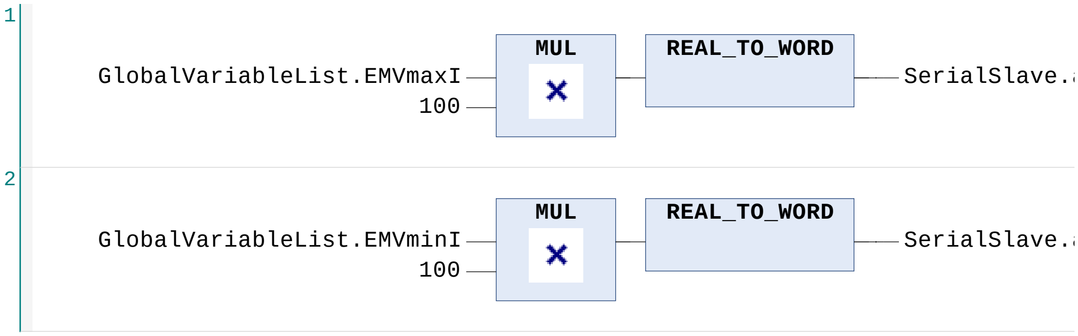
2.5 POU: TcpModbusSlave

```
PROGRAM  TcpModbusSlave
VAR
    mySimpleTcpServer   :   FbMbSimpleServerTcp  := (   xOpen        := TRUE
,
                                                        wPort        := 502 ,
                                                        utKeepAlive :=  (
xEnable         := TRUE ,

tMaxIdleTime    := T#5S ,

tInterval       := T#2S ,

udiProbes       := 5
                                                                        ) ,
                                                        bUnitId      := 1
                                                    ) ;
    myDiscreteInputs    :   ARRAY [ 0 .. 20 ]  OF  BOOL ;
    myCoils             :   ARRAY [ 0 .. 20 ]  OF  BOOL ;
    myInputRegisters    :   ARRAY [ 100 .. 200 ]  OF  WORD ;
    myHoldingRegisters  :   ARRAY [ 0 .. 20 ]  OF  WORD ;
END_VAR

```

```
mySimpleTcpServer   (   axDiscreteInputs    :=  myDiscreteInputs ,
                        axCoils             :=  myCoils ,
                        awInputRegisters    :=  myInputRegisters ,
                        awHoldingRegisters  :=  myHoldingRegisters
                    ) ;

```

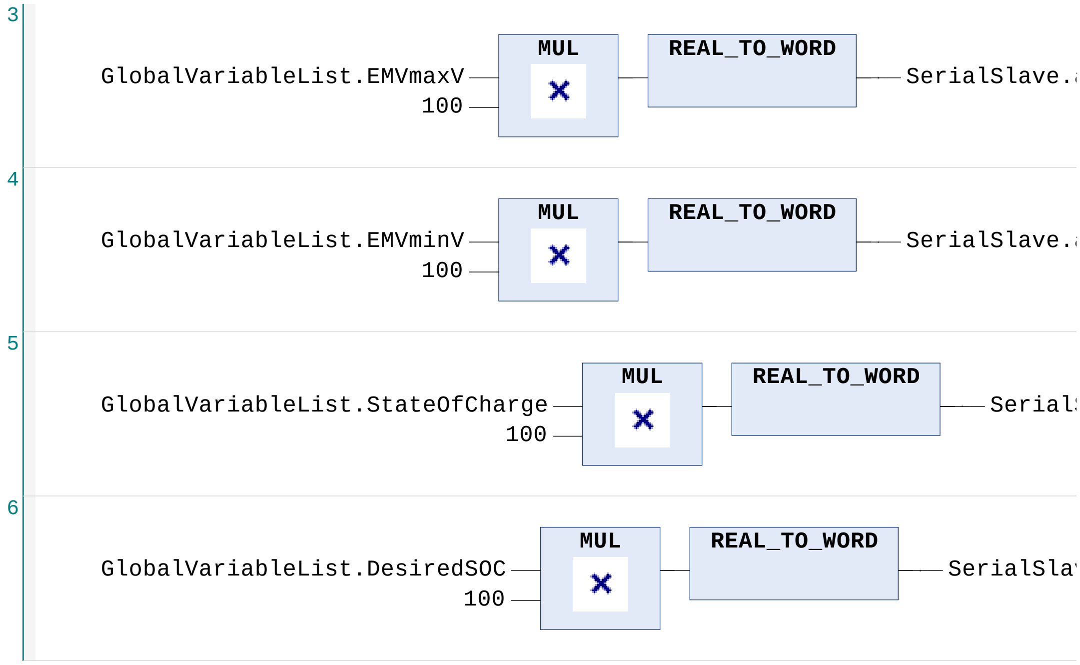
2.6 POU: VesselLogic

```
PROGRAM  VesselLogic
VAR
END_VAR

```



```
awHoldingRegisters[11]
```

```
awHoldingRegisters[12]
```


3
GlobalVariableList.EMVmaxV
100
MUL
REAL_TO_WORD
SerialSlave.
4
GlobalVariableList.EMVminV
100
MUL
REAL_TO_WORD
SerialSlave.
5
GlobalVariableList.StateOfCharge
100
MUL
REAL_TO_WORD
Serial
6
GlobalVariableList.DesiredSOC
100
MUL
REAL_TO_WORD
SerialSla

```
awHoldingRegisters[13]
```

```
awHoldingRegisters[14]
```

```
Slave.awHoldingRegisters[15]
```

```
ve.awHoldingRegisters[16]
```

2.7 Symbol Configuration: Symbols