Modeling a DC Power System in Hardware-in-the-Loop Environment

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Thesis submitted for examination for the degree of Master of Science in Technology.
Espoo 24.05.2016

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ABSTRACT OF THE
MASTER'S THESIS

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Title: Modeling a DC Power System in Hardware-in-the-Loop Environment

Date: 24.05.2016 Language: English Number of pages: 9+73

Department of Electrical Engineering and Automation

Professorship: Power Electronics

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Ever increasing requirements for increased fuel efficiency and reduced emissions on board a ship has prompted designers to turn their interest towards a distribution system where the main energy carrier is DC instead of AC. A DC power plant offers significantly reduced fuel consumption and easier integration of an increasing number of DC based sources and consumers, but also requires a more complicated control system for smart operation of the power plant. Therefore, the role of testing these control systems becomes even more important than before. This work introduces a Hardware-in-the-Loop (HIL) simulation technique for modeling and simulating a DC power plant on board a ship.

In HIL simulation technique, a control-loop is built by using components, of which some are real hardware and some are simulated. This thesis work explores the possibilities for using the HIL simulation technique to perform real-time system level tests for a DC power plant on board a ship. The interfaces required to connect the real hardware components to the HIL simulator, and that way to the software component models as required by the simulation, will be examined. These interfaces consist of fieldbus communication (IEC61850 and Modbus) and a combination of digital and analog input and output signals.

The goal of the HIL model of this work, is to offer an environment where different control schemes of the DC power system and the operation of the upper level power management and energy management systems can be tested safely and in a controlled manner. This requires that at least the controllers in the generating units are modeled using real hardware. The rest of the system can be modeled using virtual component models in the HIL software. A HIL model for modeling and simulating a complete DC power plant will be proposed and finally, the possibility to expand the model to include larger systems with more hardware will be discussed.

Keywords: Simulation, Marine, Modeling, Hardware-in-the-loop

AALTO-YLIOPISTO
SÄHKÖTEKNIIKAN KORKEAKOULU

DIPLOMITYÖN
TIIVISTELMÄ

Tekijä: Arber Haxhiu

Työn nimi: Tasasähkövoimalaitoksen Mallinnus Hardware-in-the-Loop Ympäristöön

Päivämäärä: 24.05.2016 Kieli: Englanti Sivumäärä: 9+73

Sähkötekniikan ja automaation laitos

Professuuri: Tehoelektroniikka

Työn valvoja: Prof. Jorma Kyyrä

Työn ohjaaja: TkT Pasi Pohjanheimo

Kasvavat vaatimukset polttoaineen kulutuksen ja päästöjen vähentämiseksi on saanut suunnittelijat kääntämään katseensa kohti sähkönjakelujärjestelmää, jossa sähkön jakelu kuluttajille toteutuu tasavirtana vaihtovirran sijasta. Tasasähkövoimalaitos mahdollistaa huomattavasti pienemmän polttoaineen kulutuksen ja helpottaa erilaisten DC lähteiden ja kuluttajien integroimista sähköverkkoon, mutta vaatii myös monimutkaisemman ohjausjärjestelmän voimalaitoksen älykkäälle toiminnalle. Tästä syystä ohjausjärjestelmän testauksen merkitys kasvaa jopa entuudestaan. Tämä työ esittelee Hardware-in-the-Loop (HIL) simulointimenetelmän tasasähkövoimalaitoksen mallintamiseksi ja simuloimiseksi.

HIL mallinnustavassa säätöpiiri muodostetaan komponenteista, joista osa ovat oikeita komponentteja ja osa virtuaalisesti mallinnettuja komponentteja. Tämä diplomityö tutkii HIL mallinnustavan mahdollisuuksia suorittaa reaaliaikaisia järjestelmätason kokeita laivan tasasähkövoimalaitoksesta. Rajapinnat, jotka vaaditaan oikeiden komponenttien ja HIL simulaattorin yhteen liittämiseen tutkitaan tässä työssä. Nämä rajapinnat koostuvat kenttäväyläkommunikaatiosta (IEC61850 ja Modbus) sekä digitaalisten ja analogisten signaalien yhdistelmästä.

Tämän työn HIL mallin tavoitteena on tuottaa testiympäristö, jossa tasasähkövoimalaitoksen säätöjärjestelmät ja ylemmän tason tehonhallinnan ja energianhallinnan järjestelmät voidaan testata turvallisesti ja hallitusti. Tämä vaatii, että ainakin sähköä tuottavien yksiköiden ohjaimet mallinnetaan oikeina komponentteina. Loput järjestelmästä voidaan mallintaa virtuaalisina komponentteina HIL simulaattorin ohjelmistossa. Työssä ehdotetaan mahdollinen HIL malli, jolla voidaan mallintaa ja testata koko tasasähkövoimalaitos. Lopuksi keskustellaan vielä mahdollisuuksista laajentaa mallia koskemaan laajempaa järjestelmää, jossa on enemmän oikeita komponentteja kytketty säätöpiiriin.

Avainsanat: Simulointi, Marine, Mallinnus, Hardware-in-the-loop

Preface

I wish to thank my supervisor Professor Jorma Kyyrä and my instructor D.Sc. Pasi Pohjanheimo for excellent advice and support throughout the whole thesis work. I also wish to thank Klaus Vänskä for offering me the possibility to work around a topic that has been very exciting and interesting. Special thanks to Kalevi Tervo and everyone else who, with their contribution, have made this work possible.

Finally, I wish to express my gratitude to my whole family and everyone closest to me for supporting me throughout my studies. With their support, they have helped me through hardships and provided me a joyful environment for both studying and working.

Otaniemi, 24.05.2016

Arber Haxhiu

Contents

Symbols and Abbreviations

Symbols

α	thyristor firing angle
γ	thyristor turn-off angle
$\hat{\theta}_{\psi s}$	flux linkage angle estimate
μ	thyristor commutation angle
ω_k	speed of an arbitrary rotating frame
ω_m	rotor angular velocity
ψ	flux linkage
$\hat{\underline{\psi}}_s^s$	stator flux linkage in stator coordinates
$\underline{\psi}_s^r$	stator flux linkage in rotor coordinates
$\underline{u}_s^r$	Stator voltage in rotor coordinates
d_ψ	length of the flux linkage vector
d_T	angle of the flux linkage vector
f	frequency
i	current
I_d	commutated current
J	moment of inertia
L	inductance
m_a	modulation index
n	rotor speed
n_s	stator flux speed
p	pole pair number
P_{con}	total consumed load power
P_{gi}	sum of the power generated by all generators
P_{min}	minimum available powe
R	resistance
s	slip
T	electrical torque
u	voltage
V_{ac}	anode-to-cathode voltage
V_b	circuit breaker voltage
V_d	DC voltage
V_L	line voltage
X	synchronous reactance
X'	transient reactance
X''	subtransient reactance
X_{mi}	mutual reactance to i (i=d,q,F,D,Q

Subscripts for Symbols

conv	converter
d	d-axis
D	damper in d-axis
e	electrical
F	field
L	load
m	mechanical or, if used with inductance/reactance, mutual
q	q-axis
Q	damper in q-axis
ref	reference
s	stator
σ	leakage

Abbreviations

AVR	automatic voltage regulator
Azipod®	ABB branded azimuthing podded propulsor
BJT	bipolar juction transistor
CB	circuit breaker
CH_4	methane slip
CHIL	controller hardware-in-the-loop
CO_2	carbon dioxide
CPP	controllable pitch propeller
CSI	current source inverter
CSMA/DC	carrier sense multiple access with collision detection
DNV	Det Norske Veritas
DP	dynamic positioning
DTC	direct torque and flux control
ECU	electronic control units
EMF	electromotive force
EMI	electromagnetic interference
EMS	energy management system
FET	field-effect transistor
FPP	fixed pitch propeller
GOOSE	generic object oriented substation event
GTO	gate turn-off thyristor
HFO	heavy fuel oil
HIL	hardware-in-the-loop
HMI	human machine interface
IEC	International Electrotechnical Commission
IGBT	insulated gate bipolar transistor
IGCT	integrated gate commuted thyristor
LAN	local area network
LNG	liquid natrural gas
MDO	marine diesel oil
MMS	manufacturing message specification
MOSFET	metal-oxide-semiconductor field-effect transistor
MU	merging unit
NOx	nitrogen oxides
PID	proportional–integral–derivative
PLL	phased-locked loop
PMS	power management system
PSS	power system stabilizer
PV	photovoltaic
PWM	pulse width modulatation
RFO	residual fuel oil
RMS	root mean square
SCR	silicon-controlled rectifier
SMV	sampled measured values
SSB	solid state breaker
TCP/IP	transmission control protocol and internet protocol
THD	total harmonic distortion
UPS	uninterruptible power supply
VSI	voltage source inverter

1 Introduction

1.1 Background

While AC distribution system is currently the more established system in ships today, the increasing demand for energy efficient and environmentally clean technologies has forced engineers to look for other alternative systems with both high efficiency and green technologies (reduced pollution). The search for reliable power systems with improved fuel economy and reduced emission has lately led to the introduction of DC distribution systems on board.

Due to the evolved power electronic devices, adapting a smart DC power distribution system to numerous well proven AC components and increasingly DC based energy consumers (e.g. LED lights and Heating Ventilation and Air Conditioning) and sources has been made more easily achievable. In a DC power system, the main energy carrier between the generating units and main consumers is DC. The power is generated with AC generators and immediately rectified to DC for distribution. The distribution occurs through a main DC bus and it is distributed to different AC consumers through power inverters. Due to the use of power rectifiers, the generators are not fixed to a single frequency but instead their speed can be varied for optimized fuel consumption. Additionally, a DC power system on board offers lower equipment footprint, lower weight and simpler integration of DC based energy sources and energy storage systems [1].

As with any power distribution architecture (especially relatively new ones like DC power systems on board), there are numerous design aspects which must be carefully designed to obtain optimal performance. In DC systems, particular interest include the effective power management, control of system components and protection from various fault situations. Therefore, to provide a safe and efficient DC power system on board, efficient testing of functionalities of various control and protection devices in a complete system is highly necessary. This not only helps improving the system in development stages but can often also improve the time to market of a system.

Testing a complete onboard power system and obtaining reliable results usually requires first building all the components and connecting them in a ship. Not only is this often very expensive but it is also very time consuming because it prevents designers from testing components in a complete system in different development stages. Therefore, to overcome the inconvenience of testing complete systems on board, Hardware-in-the-loop (HIL) [2] simulation is considered as a prominent solution. It enables system level testing of an onboard power system in an economically convenient environment, e.g. a laboratory.

HIL simulation is a real-time simulation technique which is often used to test different controller designs in a system. It enables evaluating how different intelligent devices respond to realistic virtual models in real time. In HIL simulation, a real-time simulator is used to model a complete system or only a part of a system. The main components with their control algorithms are connected to the HIL simulator through hardwired I/O and fieldbus communication. Together these components form a simulation loop which can be used to test the operation of a system in both normal and fault situations. Since the process itself is a virtually simulated model, the advantages of HIL simulation are significantly reduced material costs and energy consumption. Additionally, HIL simulation provides a flexible testing environment where different onboard power system configurations can be tested with a relative ease.

1.2 Purpose and Scope

The primary objective of this work is to design and model a DC power system concept of a ship in HIL environment. The goal for the HIL model is to be a simple and convenient model which can basically be built in any practical environment deemed fit by a HIL user. As a base for the HIL model, very general configurations of marine DC power systems will be used. Possibility to easily modify the configurations for different DC power system models is crucial for the flexibility of the model. Eventually, the operation of the designed HIL model will be verified in both normal operation and different known fault situations. However, the verification will not be part of this thesis work.

Before discussing the HIL model solution for a DC power system, this work will generally introduce the operation and benefits of common marine DC power systems and their components. The theory on a DC power system will help the future users of the designed HIL simulator to better understand the different aspects, e.g. component models, of the simulation.

The real-time simulator which will be used in this work as a virtual representation of a DC power system, will be obtained from a third party company. Due to the limited amount of available central processing unit (CPU) power and hardwired I/O in a HIL simulator hardware, optimizing the real hardware to manage system level testing is one of the most important tasks in this work. Theoretically, the CPU power and the number of I/O can be expanded by buying more simulator cores. However, the expensive costs of HIL simulation hardware make this solution inconvenient. Therefore, regarding the real hardware, we will only concentrate on components which are deemed necessary for testing different power generation control schemes in a DC system. This will include the main controllers in power generating units, e.g. generator voltage regulators and power rectifier controllers. Additionally, protection relays will be modeled using real hardware due to their importance on the protection of the power system. Power inverter controllers, energy storage systems and other important components in modern DC power systems will not be modeled in this work. However, an initial ground work will be done to make it easier to expand the model to eventually include these components too.

1.3 Contents of the Thesis

This work will begin by giving a general introduction to modern DC power systems and its main components. Chapter 2 will generally discuss the operation of each system component which will later be modeled in the HIL environment. Additionally, models for representing the dynamic behaviours of the electrical machines in the power system will be introduced. In Chapter 3, we will continue by introducing some common control schemes in marine power systems. This Chapter will also briefly introduce upper level management systems for controlling power generation and flow in DC power systems and manage the energy flow from different energy sources. Both Chapter 2 and 3 will serve as a good background for the reader to understand the simulation model, and the operation of its virtual components, introduced in Chapter 5.

In Chapter 3, we will introduce the simulation environment in which a DC power system will be modeled. In this Chapter, we will discuss the reasons why HIL simulation is considered as the most suitable simulation environment for testing a large system. Additionally, we will generally introduce the basics of IEC61850 communication standards and an Ethernet based Modbus communication. These two communication methods, especially IEC61850 standards, are crucial to the operation of the HIL system. They will connect the relays and upper level controllers to the HIL simulator. Finally, in Chapter 5, we will introduce the designed HIL model and in Chapter 6, we will conclude the thesis and discuss the future possibilities.

2 A DC Power System and its Components

2.1 DC Power System Architecture

Conventional marine electricity grids (Fig. 1a) usually employ alternating current as the main energy carrier between generators and large consumers. The base of the power distribution is usually a main switchboard (or 2-3 main switchboard as usually the grid is divided in two or three parts for better reliability) which distributes the electricity to different consumers around the vessel. The electricity is produced by AC generators with a diesel engine rotating a generator shaft. The frequency of the AC current in these conventional ships is usually 60 Hz (sometimes 50 Hz) and the diesel generators are synchronized to produce power with 60 Hz frequency. The propulsion motors are run with frequency converters and often transformers are used to regulate the input voltage and provide galvanic isolation between the motors and the grid.

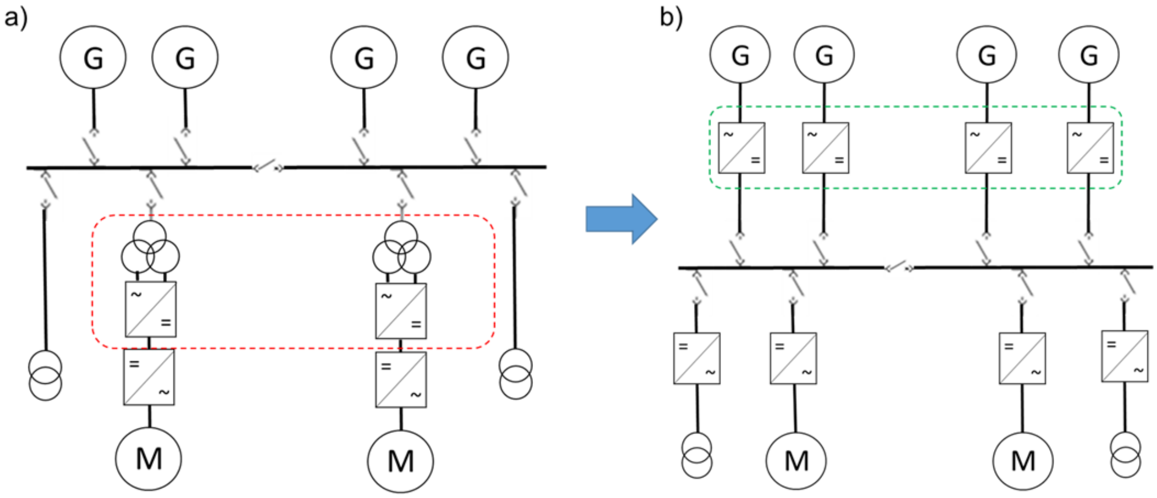

Figure 1: A typical a) AC distribution system and b) DC distribution system on board a ship. The difference between the AC and DC system is that the rectifiers are moved from the distribution units to the supply units and the large transformers are removed from the vessel.

In an attempt to produce a modern and more energy efficient power system for marine applications to compete with the ever increasing requirements for more efficient fuel economy and reduced emissions, some manufacturers have developed new power system technologies which utilize the many DC-links that already exist in all propulsion and thruster drives. In DC power systems, the direct current, instead of the AC current, is the main energy carrier between generators and large consumers. A DC power system provides an efficient system for low and medium voltage on board and is highly suitable for ice class or dynamically positioned offshore vessels [3].

A typical DC power system is illustrated in Fig. 1b). In this system, all major well proven components, e.g. AC diesel generators, inverter modules, AC motors, etc., are kept the same as in the conventional AC power systems. Basically, the only differences to the AC system are that the power rectifiers are moved from the distribution units to the generating units, large transformers are removed and naturally the distribution is DC instead of AC. The benefits of such a system are significant and the main ones will be discussed in this thesis work.

Using a DC distribution system on board a ship has proven to offer significant benefits compared to the AC distribution systems. The most significant advantage of a DC power system is the fact that the speed of the diesel generators is not locked at a certain frequency (e.g. 60Hz or 50 Hz) but instead the generators can be operated at variable speeds. This is made possible by the fact that the power generated by the AC generators is rectified to DC immediately at the supply and therefore, the speed of the diesel engines does not affect the system like in the AC distribution systems. Instead, the speed of the diesel engines can always (ideally) be optimized to the system load situation resulting into lower fuel consumption. This is illustrated in Fig. 2 where the fuel consumption of a medium speed engine is tested at different rotating speeds. The blue line represents the fuel consumption at fixed speed and the grey line at variable speed. As can be seen from this figure, the savings in the fuel consumption, especially at lower loads, can be very significant. In addition to the fuel savings, running engines at optimized speeds also leads to cleaner combustion with less build-up of soot, reduced green house gas emissions (including reduced amount of "methane slip", CH_4, which is tens of times more harmful than carbon dioxide, CO_2) and reduced maintenance costs due to less wear and tear on the engine [4].

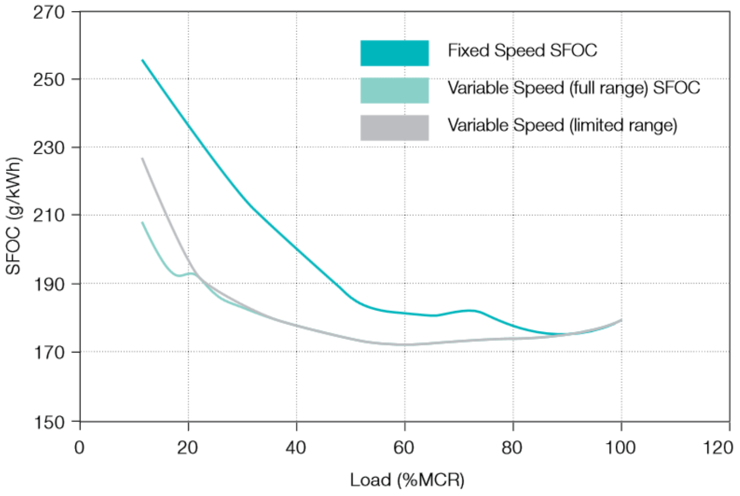

Figure 2: Specific fuel oil consumption (SFOC) as a function of RPM, expressed as maximum continuous rating (MCR), for a medium speed engine running at fixed speed vs. at variable speed [4].

In addition to the possibility for variable speed engines, the DC distribution system provides an easier solution to connect alternative energy sources (e.g. photovoltaic cells and fuel cells) and energy storages to the power system. Especially onboard energy storages have received dramatic interest in the recent years. Alternative power sources and energy storages (if charged) produce power in the form of DC which makes connecting them to the grid simpler. The control of these alternative power sources and energy storages is done through DC/DC converters and they provide several benefits to the system. Using energy storages on board (e.g. batteries and supercapacitors) can provide improved efficiency and performance for the vessel. They can have several functions on a ship, e.g. working as reserves for the generators or absorbing power variations which are caused by sudden load variations.

Other significant benefits of a DC power system are e.g. space and weight reductions which result from removing the main AC switchboards and heavy transformers, and the reduction of bus voltage distortion which is common with frequency converters. Also, e.g. for low voltage, the European Union directive 2006/95/EC defines low voltage DC between 75 – 1500 VDC and low voltage AC between 50 – 1000 VAC [5]. Therefore, a DC power plant offers increased efficiency in power transmission (requires less cable) when distributing power at e.g. 1000 VDC compared to 690 VAC. Also, since the generators only need to be synchronized to the power rectifiers but not to the grid frequency, they can be on-line much faster than in the AC grids.

2.2 Power Plant

Nowadays, the most commonly encountered power plant type on board ships is a diesel power plant which is also the plant type used in the HIL model of this work. The generating unit of a diesel power plant basically consists of a diesel engine, a synchronous generator and a power rectifier. In this section, we will introduce the basics of power generation on board a ship and how the power is, in a DC power plant, rectified to DC before distribution.

Due to the relatively less expensive price of the diesel oil and the high energy efficiency of the diesel engines, the diesel fuel has kept its popularity until today. Lately, however, the environmental awareness and the rising prices of the conventional fuels has led to the rising interest in promoting alternative fuel sources for conventional internal combustion engines. One such fuel has especially been natural gas which offers significantly lower emissions compared to the diesel fuels.

In a DC power system on board a ship, the energy is produced to the DC bus in the form of electricity using several AC generators. The diesel engines produce the shaft power to the synchronous generators which in turn transform the power of the shaft into electrical AC power. This power is rectified into DC power using power electronic converters that are mainly thyristor bridge rectifiers.

2.2.1 Combustion Engines

In the middle of the 20th century, steam turbine engines started disappearing from merchant marine vessels and by the end of 20th century, the diesel engines had more or less replaced them [6] [7, p. 110-112]. Diesel engines are combustion engines that employ the expansion of hot gases to push a piston in a cylinder and transform the pistons energy to rotate a crankshaft to produce power. The advantages of diesel engines to other thermal engines are their higher efficiency, higher power and better durability. Most marine diesel engines come with a turbocharger. These turbochargers allow a larger charge of fuel to be burned in each power stroke and thus enable obtaining greater power than with normal diesel engines [8, p. 22]. One of the disadvantages of the diesel engines is e.g. the higher cost of the engine manufacturing. However, in large ships, the cost of engine becomes insignificant compared to the cost of fuel.

Basically, based on speed, the diesel engines can be divided into three types of engines: low speed, medium speed and high speed engines. The low speed engines are big and heavy engines that usually operate on two-stroke cycles. One stroke corresponds to the up or down movement of the piston in the cylinder. Their advantage is that at low speeds their time for ignition and full combustion of the fuel is long. Also, they are lighter and easier to manufacture than four-stroke engines. The medium and high speed engines are more moderate size engines and both operate usually on four-stroke cycles. Four-stroke cycle means that there is one piston stroke for intake, compression, power and exhaust. The advantage of four-stroke cycle engines is that their emissions are lower compared to two-stroke cycle engines which has also played an important role in their rise in popularity for medium and high speed engine marine ships. However, compared to running on slower speed, a disadvantage of running on higher speed is that it gives shorter time for ignition and full combustion of the fuel. [8, p. 25-33]

Currently the most common fuel used in marine diesel engines is the residual fuel oil (RFO), commonly also referred to as heavy fuel oil (HFO). This dark residual oil is a remnant from the crude oil drilling and it contains more impurities (e.g. up to over 4 % Sulphur content) than other lighter distillates [7, p. 35]. Although, as a fuel, HFO is viscous and dirty, the competitive price has kept it as the most common fuel in use. However, according to an estimation made by Loyd's Register marine and UCL Energy Institute [9], the proportion of HFO will have a decreasing trend in the future but will still be around half of total consumption in 2030. The drop in the share of HFO will be filled by low sulphur alternatives such as marine diesel oil (MDO) or liquefied natural gas (LNG). Due it being a cleaner form of oil, MDO is gaining popularity over HFO and together these two oil fuels form the vast majority of fuels used in marine vessels [9]. However, due to improvements made in natural gas engines and the lowering price of LNG, the interest in LNG engines has increased considerably in recent years.

Since natural gas mostly consists of methane, its CO_2 emissions are much lower than those of the more traditional oil fuels, HFO and MDO. This, accompanied by the continuously decreasing price of LNG, has proven LNG to be a promising fuel instead of other oil fuels. This has led to the fact that some ships are already running purely on LNG engines but the number of these is still very small. This is partly due to the disadvantages of LNG related to fuel storing and handling. Other current disadvantages with LNG have had to do with dynamic behaviour e.g. manoeuvring and operation in heavy sea states. Due to these disadvantages, many ships have been built with dual fuel engines that can run on LNG, HFO or MDO. [10]

With a dual fuel engine, the disadvantages that occur with pure LNG engines are avoided while still managing lower emissions than with oil fuel engines discussed above. Usually, the engine works so that most of the energy is obtained from the combustion of natural gas and only a small portion of diesel oil provides the ignition. This enables much lower emissions while at the same time maintaining a good engine performance [11].

2.2.2 Power Generator

AC generators are electrical machines that transform rotating mechanical energy into electrical energy. They can be divided into two groups of machines, asynchronous and synchronous machines. However, due to the possibility for reactive power compensation and better efficiency of the synchronous machines, the majority of used generators are synchronous machines instead of asynchronous machines [12].

The main types of synchronous machines are separately excited synchronous machines, synchronous reluctance machines and permanent magnet synchronous machines. However, the main generator type used in the DC power system HIL model of this work are separately excited synchronous generators and therefore, this text we will concentrate on separately excited synchronous generators.

A cross-section of a wound salient two-pole synchronous machine is illustrated in Fig. 3. A synchronous machine consists of two main magnetic components: the stator and the rotor. The stator has a three phase winding which carries the load current. This winding is also called the armature winding. The armature winding is placed in equidistant slots on the inner surface of the core material. The rotor, which can either be a salient pole or a non-salient pole rotor, contains short circuited damper windings and a field winding (also called an excitation winding). The function of the damper windings is to dampen the effects created by the sudden electrical and mechanical changes and to lessen the effects of asymmetric loads. The function of the field winding is to produce a magnetic flux (i.e. to excite the machine) when the field winding is supplied by a DC current. [12, 13]

By supplying a DC current, I_f, to the rotor field winding, an electromagnetic field is produced around the coil with a static north and south poles, as can be seen in Fig. 3. When the prime mover (in the case of a ship, a diesel engine) rotates the rotor shaft, the magnetic poles will also rotate resulting into a rotating electromagnetic flux. When this rotating magnetic flux cuts the stator coils, it induces, according to Faradays law, an electromotive force (EMF) into the three phase armature windings and forces AC current to flow to the power system. The induced three phase current then produces its own magnetic flux, called the armature flux, which rotates at the same speed as the rotor. Together the armature flux and the excitation flux produce a resultant flux that rotates at same same speed as the rotor. If the rotor speed deviates from this synchronous speed, currents will be induced into the rotor damping windings and these currents will produce a magnetic flux that, according to Lenz's law, will oppose the change in the flux, and thus force the synchronous speed. For this reason, it is called the synchronous machine. [13]

To describe the dynamic operation of a synchronous machine, The Park two axis model (dq-model) is widely used. The dq-model of a synchronous machine is illustrated in Fig. 4. The dq-model is widely used in the simulations of transient

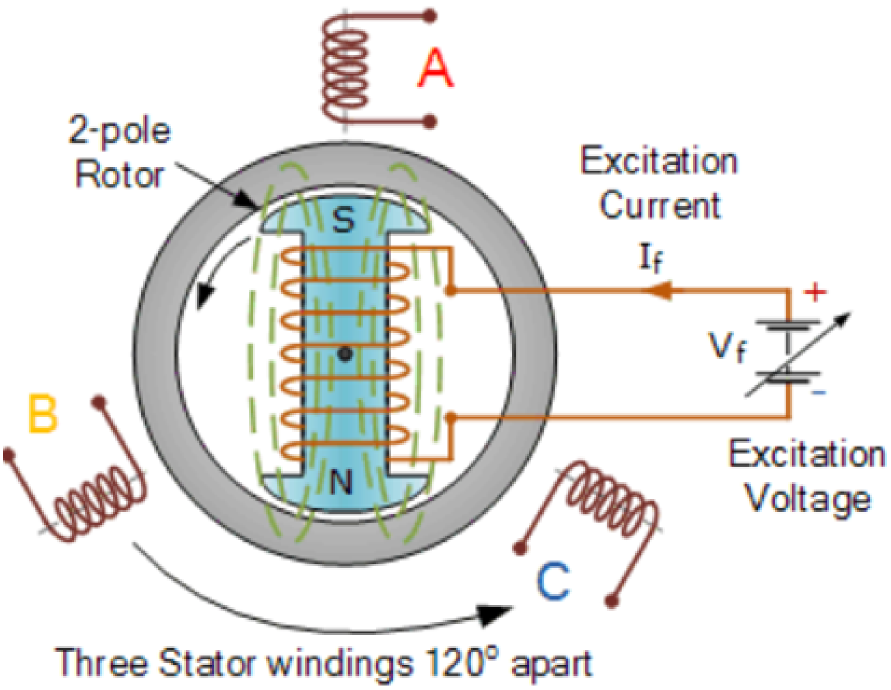

Figure 3: A cross-section of a wound salient two-pole synchronous machine [14].

phenomena in synchronous machines. In this model, d and q represent the armature windings in the d- and q-axes respectively, D and Q represent the damper windings in the d- and q-axes respectively and F represents the field winding in the d-axes.

In this model the voltage equation of the stator is divided into real and imaginary parts (i.e. $\underline{u}_s^r = u_d + ju_q$) in rotor coordinates. Apart from the reactance equations, the following equations are given as they are expressed in [12]. The reactance equations are given as they are expressed in [13]. The voltage equations corresponding to the two-axis model are

$$u_d = R_s i_d + \frac{d\psi_d}{dt} - \omega_m \psi_q, \tag{1}$$

$$u_q = R_s i_q + \frac{d\psi_q}{dt} + \omega_m \psi_d, \tag{2}$$

where R is resistance, i is current, ψ is flux linkage, ω_m is rotor angular velocity and subscripts d and q refer to d- and q-axis respectively. Since the field winding and the damper windings rotate with the rotor, their voltage equations are (Notice, damper windings are short circuited)

$$u_F = R_F i_F + \frac{d\psi_F}{dt}, \tag{3}$$

$$0 = R_D i_D + \frac{d\psi_D}{dt}, \tag{4}$$

$$0 = R_Q i_Q + \frac{d\psi_Q}{dt}, \tag{5}$$

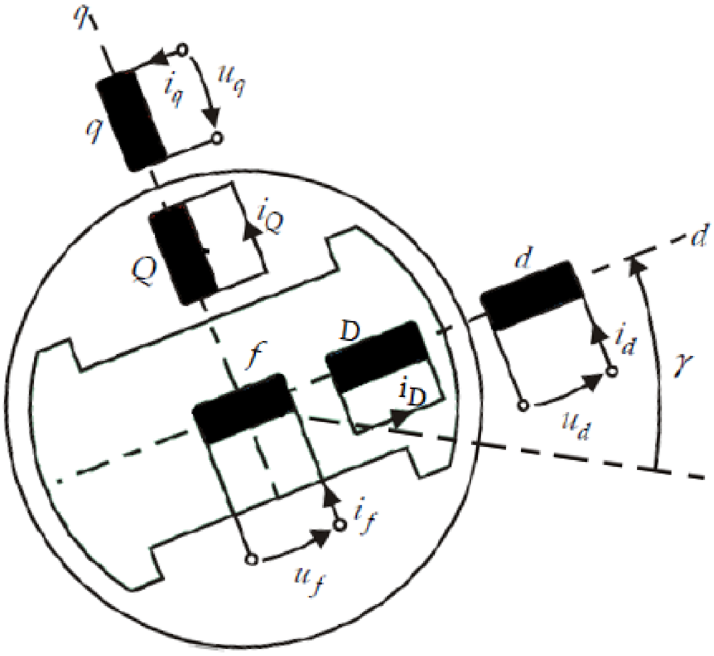

Figure 4: A two-axis model of the synchronous machine.

where subscript F refers to field winding and subscripts D and Q refer to damper windings in d- and q-axis respectively. Further, the stator flux linkage equation is also divided into real and imaginary parts (i.e. $\underline{\psi}_s^r = \psi_d + j\psi_q$). The flux linkage equations are

$$\psi_d = L_d i_d + L_{md} i_F + L_{md} i_D, \tag{6}$$

$$\psi_q = L_q i_q + L_{mq} i_Q, \tag{7}$$

$$\psi_F = L_{md} i_d + L_F i_F + L_{md} i_D, \tag{8}$$

$$\psi_D = L_{md} i_d + L_{md} i_F + L_D i_D, \tag{9}$$

$$\psi_Q = L_{mq} i_q + L_Q i_Q, \tag{10}$$

where L_i $(i = d, q, F, D, Q)$ are the self inductances of the corresponding windings and L_{mj} $(j = d, q)$ are the mutual inductances.

Often when analysing the dynamic behaviour of the synchronous machine in fault situations, it is beneficial to use the synchronous reactance (X), the transient reactance (X') and the subtransient reactance (X'') values of the machine. These reactances describe the sudden changes in the fundamental AC components of the armature voltage and current. Using these parameter values, it is easy to determine the traditional time constants of the synchronous machine. However, when calculating these values, an assumption is often made that mutual reactances between the windings on the d-axis are equal and of the magnitude of the d-axis magnetizing inductance $L_{dF} = L_{dD} = L_{FD} = L_{md}$. The reactances are then

$$X_d^{''} = X_{\sigma s} + (\frac{1}{\frac{1}{X_{md}} + \frac{1}{X_{\sigma F}} + \frac{1}{X_{\sigma D}}}), \tag{11}$$

$$X_d^{'} = X_{\sigma s} + (\frac{1}{\frac{1}{X_{md}} + \frac{1}{X_{\sigma F}}}), \tag{12}$$

$$X_d = X_{\sigma s} + X_{md}, \tag{13}$$

$$X_q^{''} = X_{\sigma s} + (\frac{1}{\frac{1}{X_{mq}} + \frac{1}{X_{\sigma Q}}}), \tag{14}$$

$$X_q = X_{\sigma s} + X_{mq}, \tag{15}$$

where subscript σ denotes leakage reactance, X_{md} and X_{mq} are the magnetizing reactances for d and q axis respectively and $X_{\sigma Q}$ is the q-axis leakage reactance of damper winding.

The electrical torque of a three phase machine is given by

$$T_e = \frac{3}{2} p Im\{\underline{\psi}_s^* \underline{i}_s\} = \frac{3}{2} p(\psi_d i_q - \psi_q i_d), \tag{16}$$

where p is the pole pair number of the machine. The equation of motion of the rotor is

$$\frac{d\omega_m}{dt} = \frac{p}{J}(T_e - T_L) \tag{17}$$

where J is the moment of inertia and T_L is the load torque which, in the case of ships generators, is the shaft torque of the diesel engine.

2.2.3 Power Rectifier

Since the generators and motors used in a DC power system are AC machines, they require AC output and input. Therefore, to produce DC current to the main DC bus and AC current from the DC bus, the current has to be converted using power electronic circuits. The main components in these circuits are usually diodes, thyristors or transistors. This section will briefly introduce the main components used in power electronic converters after which the structure and the operation of a power rectifier will be discussed.

A diode is a semiconductor component with two electrodes called anode and cathode. The basic functionality of a diode is to conduct electricity only in one direction. Generally, the diode conducts when the voltage difference between the anode and the cathode is higher than the diode forward breakover voltage (typically 0.6 V for silicon diodes). This, however, does not hold if the voltage of the cathode is much higher than that of the anode, in which case the diode will conduct in reverse direction.[15, p. 26]

A transistor is a three layer semiconductor device that can be used as a signal amplifier or as an open circuit switch. Transistors can be divided in two groups: bipolar junction transistors (BJT) and field-effect transistors (FET). Nowadays, however, in new power electronic devices, the field effect transistors e.g. metal-oxide-semiconductor field-effect transistor (MOSFET) and insulated gate bipolar transistors

(IGBT) are the more common ones. The basic functionality of the transistors as a switch is that by supplying them with base (for BJT) or gate (for FET) currents, they turn on and conduct. When the base or gate current supplying is ended, the transistors turn off. More on transistors is found from [15, p. 72].

The equivalent circuit and the symbol of an IGBT is shown in Fig. 5. The IGBT operates in such a way that applying it with a gate signal, turns on the MOSFET. That way, the current starts flowing through MOSFET to the base of the PNP transistor and turns it on creating a current flow between the collector and the emitter. The IGBT turns off when the gate signal is no longer applied. The NPN transistor is attempted to keep switched off using resistances so that the two transistors, PNP and NPN, would not form a thyristor. The advantages of IGBTs are their easy controllability, moderate losses and frequency band of up to 5-150 kHz. [15, p. 99].

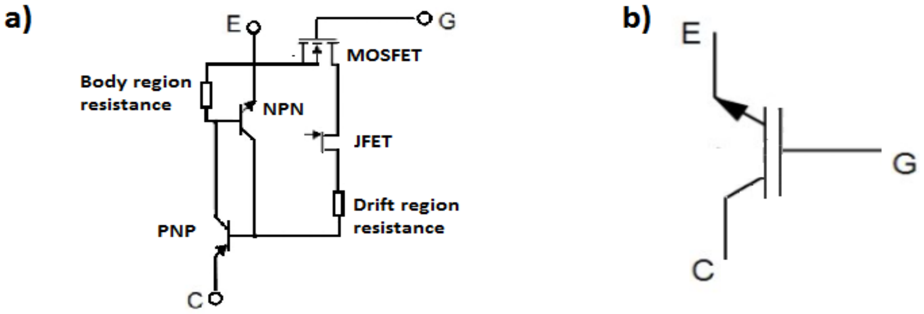

Figure 5: a) an equivalent circuit and b) a symbol of the IGBT.

A thyristor A.K.A silicon-controlled rectifier (SCR) is a three junction device (Fig. 6) where the outer two regions are strongly doped and the two in the middle are lightly doped. A thyristor can operate as a rectifying diode or an open-circuit switch. Like a diode, the thyristor has an anode and a cathode, but unlike a diode, it also has a third terminal called the gate which is used to control the thyristor. An equivalent circuit of the thyristor, containing two BJT:s, is shown in Fig. 6c. By applying a positive anode-to-cathode voltage V_{ac} on the gate, the transistor Q_1 (NPN) turns on. This on turn supplies a negative current to the gate of transistor Q_2 (PNP) and causes it to turn on as well. When both transistors are on, current passes from the anode to the cathode and the thyristor conducts. It can be turned off by applying a negative anode current or a negative V_{ac} until the charge carriers in the two middle sections are recombinated or spread off. [15, p. 11] [16, p. 88]

Apart from SCRs, there also exists different kinds of thyristors, e.g. gate turn-off thyristors (GTO) or integrated gate commuted thyristors (IGCT). GTOs are thyristors that can be turned on like SCR:s by applying a positive gate current to it, but they can also be turned off by applying a negative gate current. An IGCT is basically an upgraded version of the GTO. It operates the same way as a GTO except that on turn off, the negative gate current is increased rapidly (1 μs) to the same value as the anode current. The benefit of the rapid increase is that the cathode current reduces to zero without it concentrating on the middle of the cathode. This

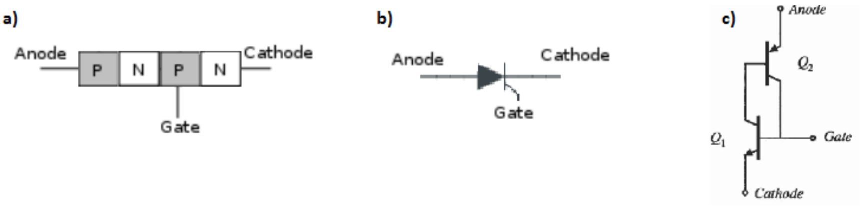

Figure 6: a) a structure, b) a symbol and c) an equivalent circuit of the thyristor.

increases the voltage endurance of the thyristor.

Thyristor converters are power electronic circuits that provide controlled conversion from AC input to variable DC output (or vice versa). A six-pulse thyristor converter circuit is shown in Fig. 7. In this circuit, the output current is expressed as an ideal current source for simplicity but in reality, an ideal output current is never achieved. The inductances L in the input of the bridge exist because of the inductances in the line prevent the instantaneous current commutation. These line leakage inductances define the interval of the current commutation between the thyristors [17, p. 124].

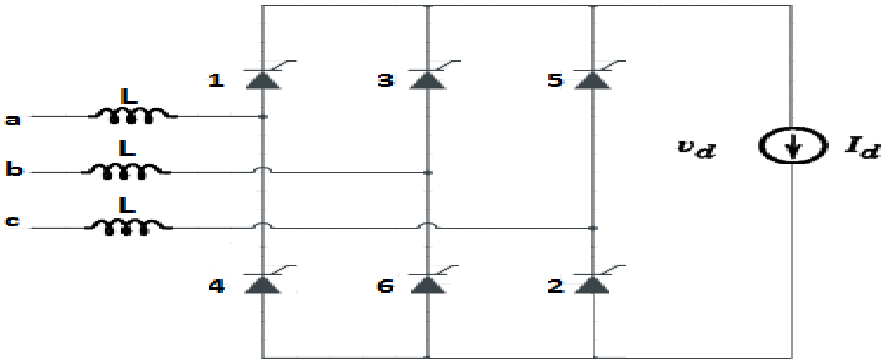

Figure 7: A six-pulse thyristor bridge.

The thyristor bridge in Fig. 7 operates in such a way that only two thyristors on different commutation groups conduct at a time. One on the upper half and one on the bottom half of the bridge. As was previously mentioned with thyristors, they turn on by applying a gate signal on them when the voltage across them is in forward direction and turn off when the current through them crosses zero and tries to go negative. By controlling the instant at which the gate signals are applied with respect to the AC voltage waveforms, the magnitude of the DC output can be controlled.

The instant, at which the gate signal is applied, is called the firing angle α. Notice, that by using a firing angle $\alpha = 0$, the thyristors would operate like diodes. In fact, the AC-DC conversion could also be achieved with diodes (by replacing the thyristors with diodes) but the conversion would no longer be controlled. Instead, the DC output would always be the same, depending on the AC input. Therefore, a diode bridge could be thought of as a special case of a thyristor bridge where the firing angle is $\alpha = 0$.

Theoretically, the firing angle α could be chosen freely between $[0 \leqslant \alpha < 180]$. However, in practice it is important to take into account both the time it takes for the current commutation (commutation angle μ) and the time it takes for a thyristor to recover from the turn-off (turn-off angle γ) [15, p. 47]. Therefore, the commutation angle and the turn-off angle usually determine how far angle α can be increased. A minimum angle, that should be left for safe commutation, is

$$\beta = \mu + \gamma \tag{18}$$

The waveforms for a thyristor bridge with a firing angle α are shown in Fig. 8. To understand the operation of the thyristor bridge, consider a situation where thyristors 1 and 2 have been conducting previously. At angle α, thyristor 3 is triggered (thyristor 3 is already forward biased at this point) and during the commutation interval μ, both thyristors 1 and 3 conduct. At instant $\alpha + \mu$, the commutation is over and thyristor 1 no longer conducts. Since this is a six-pulse bridge, the triggering occurs every $2\pi/6$ intervals. Therefore, at interval $\pi/3 + \alpha$ thyristor 4 is triggered and so on.

The DC voltage [18, p. 42] on the supply side of the six-pulse thyristor rectifier is given by

$$V_d = 1.35 V_L cos(\alpha) - \frac{3XI_d}{\pi}, \tag{19}$$

where V_L is the rms line voltage, I_d is the commutated current and $X = \omega L$ is the line reactance. Notice that according to (19), if the firing angle α is higher than $90°$, the first term of the DC voltage becomes negative. This means that the bridge no longer operates as a rectifier but instead as an inverter meaning that the power moves from DC to AC. Therefore, to operate in the rectifier mode, the firing angle must be $[0 \leqslant \alpha < 90]$.

The waveform of the output DC voltage is shown in the bottom waveform of Fig. 8 as bold line. As can be seen in this figure, the DC voltage is not pure but instead there occurs some ripple which is usually unwanted. To reduce this ripple, good filtering in the output is needed. A good way to reduce the ripple is using combinations of bridge structures to increase the number of pulses in the bridge. This decreases the amplitude and increases the frequency of the ripple which makes it easier to filter. [17, p. 128]

Another way to perform the AC/DC conversion would be to use transistors (nowadays mainly IGBT:s for medium and high power drives) instead of thyristors. The benefits of IGBTs over thyristors are better controllability and higher switching frequency when the used power is up to 1 MW. At higher powers, however, the thyristors are better suited due to their better voltage and current endurance. [15, p. 99]

Due to the constant switching of the converters, some electromagnetic interference (EMI) and line power quality problems arise. Firstly, fast changes in the voltage (du/dt) create radiated EMI and also, due to parasitic coupling capacitors, some conducted EMI. Similarly, fast changes in the current (di/dt) create conducted EMI due to parasitic mutual inductances. To reduce these EMI problems, proper shielding, filtering and grounding is required [17, p. 148].

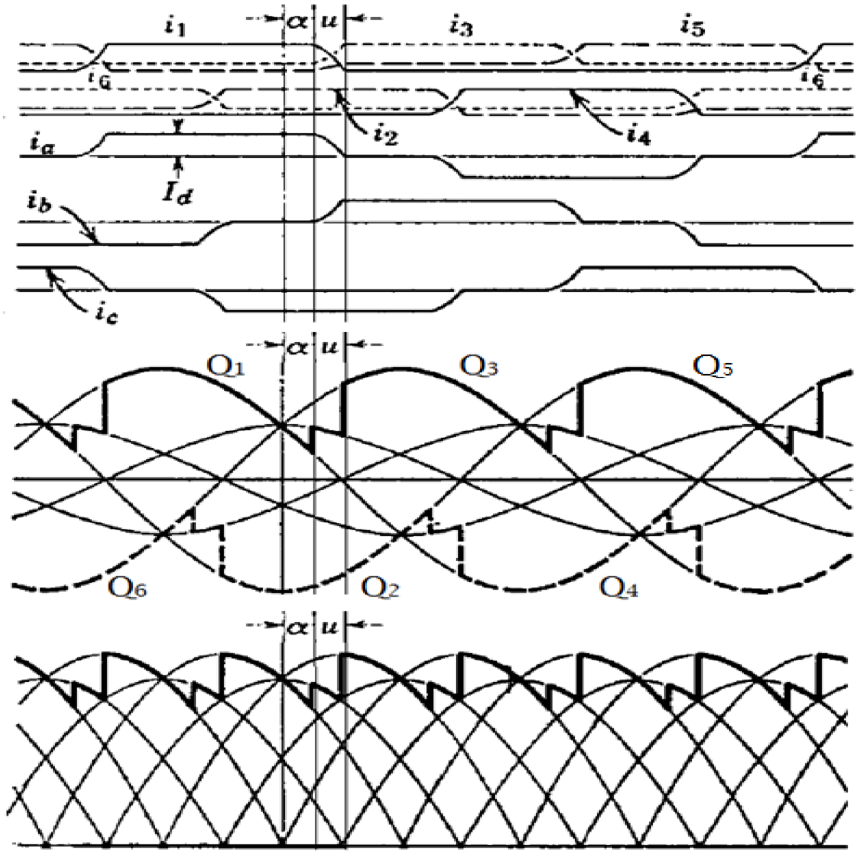

Figure 8: The waveforms of a six-pulse thyristor bridge. The current waveforms on the top represent the thyristor currents and the line currents, the waveform in the middle represents the phase voltages, and one in the bottom represents the output DC voltage. [18, p. 40] (edited).

Secondly, due to the harmonics caused by the switching of the semiconductor components, power quality problems occur. On the AC side, the switching results to drawn AC current being non-sinusoidal [18, p. 59]. This non-sinusoidal current consists of a fundamental current and harmonics of order $pn \pm 1$ (p is the number of pulses and n = 1,2,3. . .). The waveforms of the seven lowest harmonics of the primary current of a ΔY-connected transformer of the 3-pulse bridge and their sum is shown in Fig. 9. On the DC side, the switching causes harmonics of order pn.

Basically the difference between harmonics in the AC side and harmonics in the DC side is that former ones are harmonic currents and latter ones are harmonic voltages. The current harmonics on the DC side can be obtained when the impedance corresponding to the specific frequency on the DC side is known. Similarly, the voltage harmonics on the AC side are obtained when the impedance corresponding to the specific frequency on the AC side is known. These harmonics are usually undesired and cause several problems in a power system. E.g. the current distorted by a power electronic converter flows through line source inductance and thus distorts distribution bus voltage which in turn may cause problems to sensitive loads connected to it. Additionally, harmonic currents create additional losses to the line equipment, cause extra heating of the equipment and cause torque pulsations in electrical machines. Therefore, filtering higher order harmonic currents is usually highly desirable in power systems. [17, p. 149].

Since the harmonics in a line are usually undesired and may cause serious quality problems, standards exist that require a specific power quality. One way to express the quality of the line is total harmonic distortion (THD) at a certain point:

$$THD = \frac{\sqrt{\sum_{n=2}^{\lim} {V_n}^2}}{V_1} = \frac{\sqrt{\sum_{n=2}^{\lim} (I_n * h\omega L_{s1})^2}}{V_1} \tag{20}$$

where V_1 is the fundamental voltage, $V_n(i = 1, 2, 3...)$ are the harmonics and $Ls1$ is the AC source inductance. E.g. Det Norske Veritas (DNV) states that the maximum THD in the voltage at the point of common coupling for distribution systems on board a ship should normally not exceed 5 % of the fundamental voltage [6]. Harmonic analysis studies are often required for documenting the harmonic distortion level and find methods to reduce the harmonic distortion.

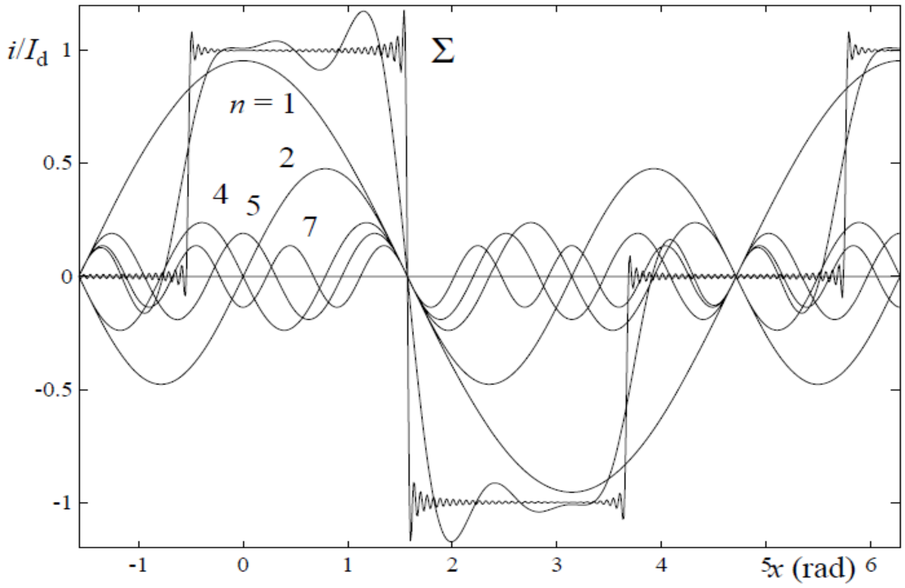

Figure 9: The seven lowest harmonics of the primary current of a ΔY-connected transformer of the 3-pulse bridge and their sum. The sum of one hundread harmonics is also shown. [18, p. 61].

2.3 Electric Power Distribution

In a DC power system on board a ship, various DC links around the vessel are merged and the power is distributed through a single DC circuit. The power is produced by diesel generators and then rectified by thyristor rectifiers (or generally with power electronic converters). The power is then distributed to consumers through a common DC bus.

Typical configurations of a DC power system are centralized and fully distributed systems shown in Fig. 10. In the centralized multi-drive system (Fig. 10a), all converter modules exist in the same lineup at the same place where the main AC switchboards are usually placed in the AC distribution. In the distributed system (Fig. 10b), the converters are located as near as possible to the respective power source or the load. [19]

Compared to an AC system, the major advantages of both these DC power system architectures are that the main AC switchboards and propulsion transformers can be omitted. Instead, all power is fed directly or via a rectifier into the common DC bus that distributes it to the consumers through a power inverter. For better reliability, the DC bus is separated into two or more sections using bus-tie breakers which enables running only half of the power plant in case of a fault situation. Each load is fed by a separate inverter unit. The 400 VAC distribution, e.g. hotel loads, is fed by specific island converters which are designed to feed clean power to these more sensitive circuits. Between the inverters and the AC distribution, transformers exist to regulate the voltage into the appropriate level and produce galvanic isolation between them.

A DC power system on board a ship offers advantages in both space and weight savings and the possibility for a more flexible placement of the electrical equipment which comes from omitting large electrical equipment like thruster transformers. In addition to this, since the power in the grid is DC, reactive power flows and voltage drops due to them are eliminated.

2.3.1 DC Current Breakers

A circuit breaker (CB) is a switch which is designed to be able to interrupt the flow of the current and dissipate the energy stored in the circuit inductances while at the same time having as low on-state conduction losses as possible [20]. Its purpose is, in fault situations e.g. short circuits, to isolate the faulty section from the rest of the circuit and that way protect the rest of the system from high currents.

Both AC and DC currents have specific circuit breakers designed for them. However, due to the nature of the DC current, interrupting it is slightly more difficult than interrupting AC current. This is due to the fact that with AC currents there occurs a natural zero crossing every half a cycle. In case the CB is opened, an arc is generated. This arc will remain active until the current goes to zero which, in a 60 Hz system, happens every 8.3 ms. Since the DC current is continuously constant, the DC CB must open very quickly and be physically strong enough to produce a sufficient dielectric withstand for arc extinction. This makes DC CB:s significantly larger and more expensive than its AC counterparts.

To demonstrate the operation of a CB, a CB in a simple DC grid is shown in Fig. 11. In case of a short circuit in the system, The voltage source views the circuit as a source impedance, CB and a load impedance. By letting L and R represent the total inductance and resistance of the circuit respectively, the DC voltage of the circuit

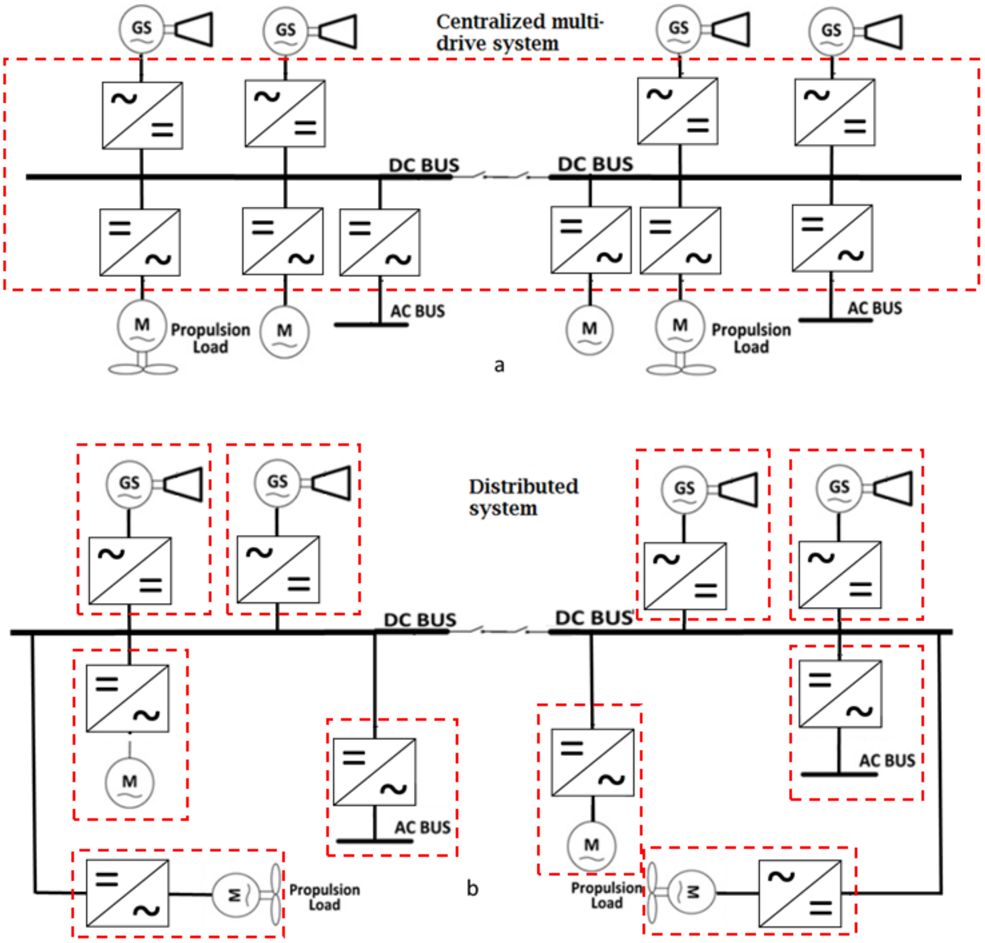

Figure 10: Typical DC power system architectures. a) A centralized multidrive system and b) a distributed system. [19]

can be represented by

$$V_{dc} = L\frac{dI}{dt} + RI + V_b, \tag{21}$$

where V_b is the voltage over the CB and I is the current flowing in the circuit. By rearranging Eq. (21) we obtain the change in the current

$$\frac{dI}{dt} = \frac{1}{L}(V_{dc} - RI - V_b). \tag{22}$$

To guarantee the arc extinction, it is necessary that $\frac{di}{dt} < 0$. Therefore, to be able to drive the fault current to zero, breaker voltage V_b must be higher than $(V_{DC} - RI)$. Eq. (22) shows us that the time it takes to clear the fault current depends on the voltage across the breaker and the size of the inductive load. Once fault current is forced to zero, the CB must act as an isolator to prevent the current from flowing until the CB is closed again. [20, 21]

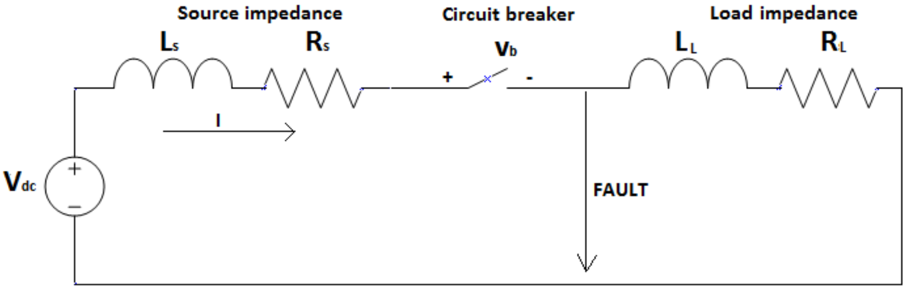

Figure 11: A basic DC circuit with a DC breaker

Although the basic operating principles of all circuit breakers are similar, there exist different types of technologies developed for various operating conditions. They can be divided into arc based (electro-mechanical) circuit breakers and solid state breakers (SSB).

Common arc based CBs use electromechanical contacts for circuit isolation. Once the current is interrupted, they create an arc to dissipate the stored energy. Arc based CBs have very low on-state losses but they also have relatively long tripping times (100 ms) which would not be favourable with sensitive loads [22]. Due to the very short time constants of the fault currents and sensitive capacitor banks, the circuit breaking in the DC links needs to be executed very rapidly. Therefore, conventional arc based CBs are not suitable for the current breaking in the DC links. Instead, they can be used in those parts of the system where the clearing time can be longer.

SSBs are switches where the role of the electro-mechanical contact is replaced by fast switching power semiconductor devices like IGBTs and IGCTs. Due to the fast switching abilities (i.e. microsecond response time [23]) and controllability of the semiconductor devices (see. 2.2.3), the line current can be limited to very low levels. This limits the system energy, thus making it easier to be managed and e.g. reduces the cabling capacity design. In addition to this, due to the missing of the electric arc, the SSBs can operate in silence and they do not emit gas nor flame. However, some drawbacks for the SSBs are their relatively high on-state losses, increased EMI due to fast switching and lack of a mechanical/galvanic isolation in the opened state. In addition to this, currently a major disadvantage of the SSBs is the high price of semiconductor devices. Nevertheless, the falling prices would make them strong candidates for future use in marine systems [20, 23]

Two simple bidirectional SSB topologies, using IGCTs and IGBTs, are shown in Fig. 12. To understand the operation of an SSB, one can think of a situation, like the one in Fig. 11, where the CB is replaced with an SSB. In normal operation the semiconductor devices allow the free flow of the current. In case of current interruption, these switches are turned off to block the path of the current. Parallel to the switches is connected a metal oxide varistor [15, p. 119]. When the switch is turned off, this varistor is used to dissipate stored energy in the circuit inductance. While turned off, the SSB provides a dielectric isolation to prevent the current flow until the semiconductor is turned back on. More on different SSB topologies and their cost differences is found from [23–25]

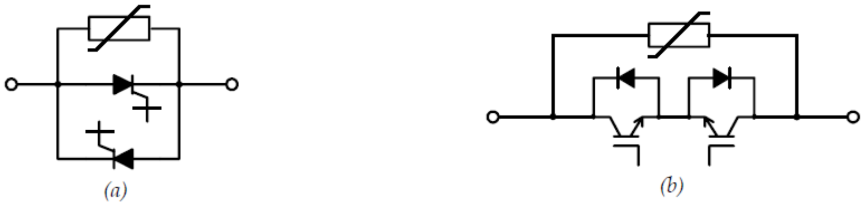

Figure 12: A basic bidirectional SSB with a) IGCT:s and b) IGBT:s

2.3.2 Grid Sections and Protection Relay

Normally, the main DC bus is divided in two, three, or four sections to obtain redundancy requirements of the vessel. That way, even if one of the sections fails, e.g. due to a short circuit, the rest of the system will continue safe operation. A common configuration in onboard power systems is a two-split configuration where generator capacity and load is equally shared on both sides. Therefore, should a major failure in one section cause a partial blackout, the healthy section will still be able to function safely and that way only 50 % of the generator capacity and loads will be lost.

Section 2.3.1 introduced common DC current breaking devices which are currently used in DC power systems. Preventing severe faults flowing from different parts of the DC system requires smart use of DC switches. The time which is allowed before a fault must be cleared depends largely on which part of the system the fault occurs. The converters connected to the DC links have integrated capacitor banks which support the DC link voltage and reduce the ripple that is produced by the AC-DC converter (see 2.2.3). The converters rely on these capacitor banks for operation. Therefore, any fault must be cleared quickly. Also, due to the capacitive nature of the DC links, the fault current path has a very low series inductance. Due to this, the fault currents have very short time constants and therefore can quickly rise to high levels within very short time after a fault. This means that the fault needs to be cleared very quickly, usually in the range of a few microseconds to a millisecond. Therefore, this requires the use of solid state components. On the other hand, on those parts of the DC system which are characterized by fault currents with longer time constants, slower-acting protection can be used. In these parts, we use mechanical DC breakers which were introduced in 2.3.1. Usually to control these breakers, protection relays are used.

A relay is a device that is primarily used to open circuit switches in fault situations and close them after the fault is cleared. Originally, the relays were designed as simple electromechanical devices. Nowadays, however, the relays are often microprocessor based intelligent devices that perform different functions for protection (e.g. overcurrent and earth-fault protection), control, measurement and supervision in utility and industrial power distribution systems. To be able to perform all these tasks, the relay functions together with current transformers and circuit breakers. In normal conditions, the relays are not usually required to function except for maybe transmitting current and voltage information to the rest of the power system controllers. However, in case of fault conditions, the relays must be able to handle these serious conditions and prevent damage to the grid, or devices in it, from happening.

The benefits provided by the modern microprocessor based relays are higher accuracy, reduced space, lower equipment and installation costs and wider application and setting capabilities. The relays offer remote and peer-to-peer communication, data acquisition, fault location and event recording which are all basically essential to the smart grids of today. Nowadays, especially relays that fully support the IEC61850 standard for communication and interoperability of substation automation devices are gaining interest in designing of safe and efficient power systems. [26]

2.3.3 Power Inverter

An inverter is a power electronic circuit that transforms a DC input into an AC output. They are vastly used in AC-motor drives, uninterruptible power supplies (UPS) and alternative power sources, e.g. photovoltaic (PV) panels and fuel cells. The purpose of an inverter is to produce a sinusoidal voltage whose amplitude and frequency can be controlled. In an onboard DC power system, inverters are used to transform the DC voltage of the DC bus into an AC voltage to feed the propulsion motors and to supply the 400 VAC distribution.

Inverters can basically be classified into two types of inverters, voltage source inverters (VSI) or current source inverters (CSI), depending on whether they require DC voltage or DC current as input. The CSIs are usually thyristor bridges that are fed with adjustable DC current and whose output is AC current that is independent of the load. The VSIs are usually IGBT bridges (or alternatively e.g. MOSFET bridges) that are fed with a variable (or constant) DC voltage and whose output is AC voltage that is independent on the load. Of these two inverter types, the VSIs are more efficient, have faster dynamic response, are more reliable and are smaller in size than the CSIs [27]. Due to the extensive use of VSIs in motor drives, this text will concentrate on VSIs. However, the CSIs are in many ways somewhat dual to VSIs [17, 18].

An IGBT bridge inverter is shown in Fig. 13. It consists of three legs which each consist of two IGBTs. Since the IGBTs cannot withstand reverse voltage, feed back diodes are connected in antiparallel with the IGBTs to allow a free reverse current flow. These diodes are often called the freewheeling diodes. An input capacitor is usually used to achieve a stiff voltage source in the input of the inverter. Both the IGBTs and the diodes must withstand the DC link voltage V_d. The half-bridges are mutually phase shifted by $2\pi/3$ angle for them to produce a three phase voltage for the load.

The idea of the three-phase IGBT inverter operation is that IGBT switches are controlled alternately to generate an output voltage that resembles a sinusoidal waveform. Theoretically, the switches in each leg are switched in such a way that

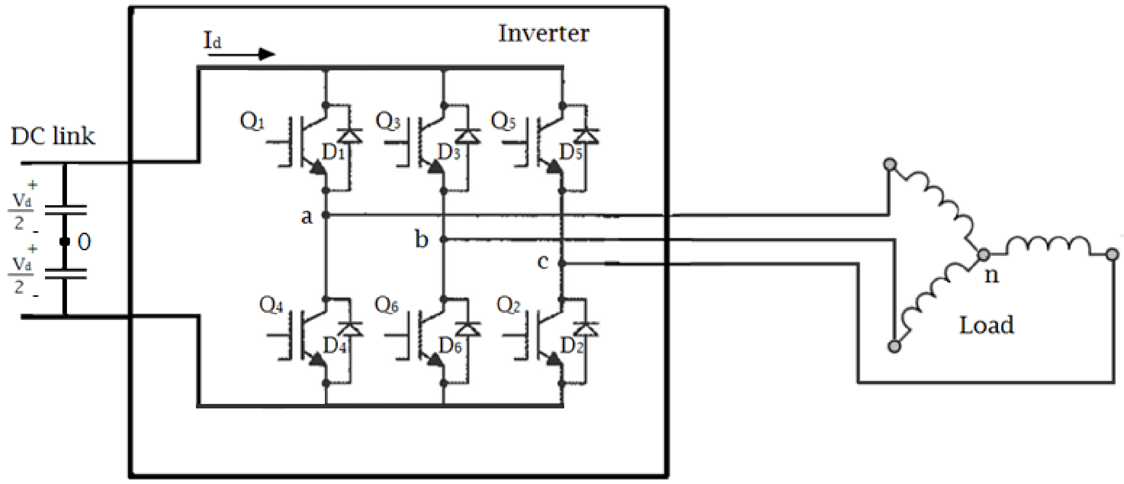

Figure 13: An IGBT bridge inverter with a capacitor bank and a three-phase load.

when one of the switches is on, the other one must be off. However, in practice since the switching does not occur instantaneously, the switches are both kept off for a short period of time (called the blanking time) to avoid short-circuiting of the DC input. The inverter output voltage is square shaped but it reminds a sinusoidal wave.

Nowadays, the most common inverter types are pulse width modulated (PWM) inverters which are also mainly used for controlling the propulsion motors in onboard power systems. In PWM inverters, the voltage amplitude and the frequency are controlled simultaneously using a PWM technique. Several different PWM methods exist [17, p. 210] of which two common methods in industrial converters are sinusoidal PWM and space vector PWM.

In sinusoidal PWM the modulation is achieved by comparing a sinusoidal wave

$$m(t) = m_a sin(\omega_0 t), \tag{23}$$

where m_a is the modulation index, to a triangle wave as shown in Fig. 14 (for a single phase). In Fig. 14 the upper switch is on when the sinusoidal wave is higher than the triangle wave and the lower switch is on at other times. This way the average value of the output voltage alters sinusoidally and the frequency of the output voltage is that of the sinusoidal wave. The advantage of the sinusoidal PWM is its relative simplicity. However, a disadvantage is that the sinusoidal PWM is effective only when the frequency of the triangle wave is higher than that of the fundamental component of the sinusoidal wave. At higher frequencies of the fundamental wave, the sinusoidal PWM loses much of its effectiveness because the allowed switching frequency limits the number of pulses in a half section [17, p. 165].

The space vector PWM is an advanced and computationally intensive PWM method that is possibly the best PWM technique in regards to performance characteristics. Nowadays, the space vector PWM is the most used PWM technique in high performance motor drives.

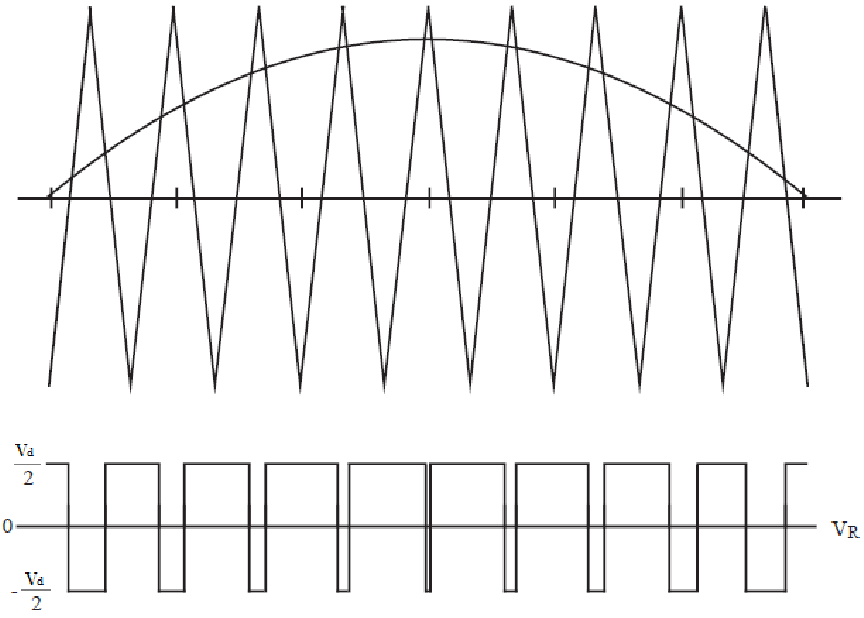

Figure 14: The determination of the switch position of one phase in sinusoidal PWM [18].

In space vector PWM the output voltage is treated as a constant amplitude voltage rotating at constant frequency ω. The space vector [12] of the output voltage is

$$\underline{v}_s = \frac{2}{3}(v_1 + \underline{a}v_2 + \underline{a}^2 v_3), \tag{24}$$

where $\underline{a} = 1\underline{/120^\circ}$. The reference voltage is approximated by a combination of eight switching patterns (V_0 to V_7). These space vectors are defined so that V_0 equals the state where switches $Q_4Q_6Q_2$ are on, V_1 equals the state where switches $Q_1Q_6Q_2$ are on and so on. These space vectors are shown in Fig. 15 (notice that V_0 and V_7 are zero vectors at the origin). The big circle represents the pure sinusoidal reference voltage. Using the space vectors, it is tried to follow this circle and obtain as sinusoidal output voltage as possible. As can be noticed from Fig. 15, the higher the used switching frequency the sinusoidally purer the output voltage. [17, 18]

The advantages of high frequency PWM converters are almost pure sinusoidal output current waveform, fast control response and lower torque ripple in the motor. With a PWM converter, lower order harmonics can be minimized which results into easier filtering in the output. Since only the higher order harmonics need to be filtered, the sizes of the used filter components are also significantly smaller. [28]

The disadvantages of the PWM converter have mainly to do with EMI problems and switching losses due to the high switching frequency. The high dv/dt and di/dt can cause EMI problems that can have a negative effect on the nearby apparatus. Therefore, it is very important to use good filtering to avoid EMI related problems. In addition to this, due to the overlapping of voltage and current during switching,

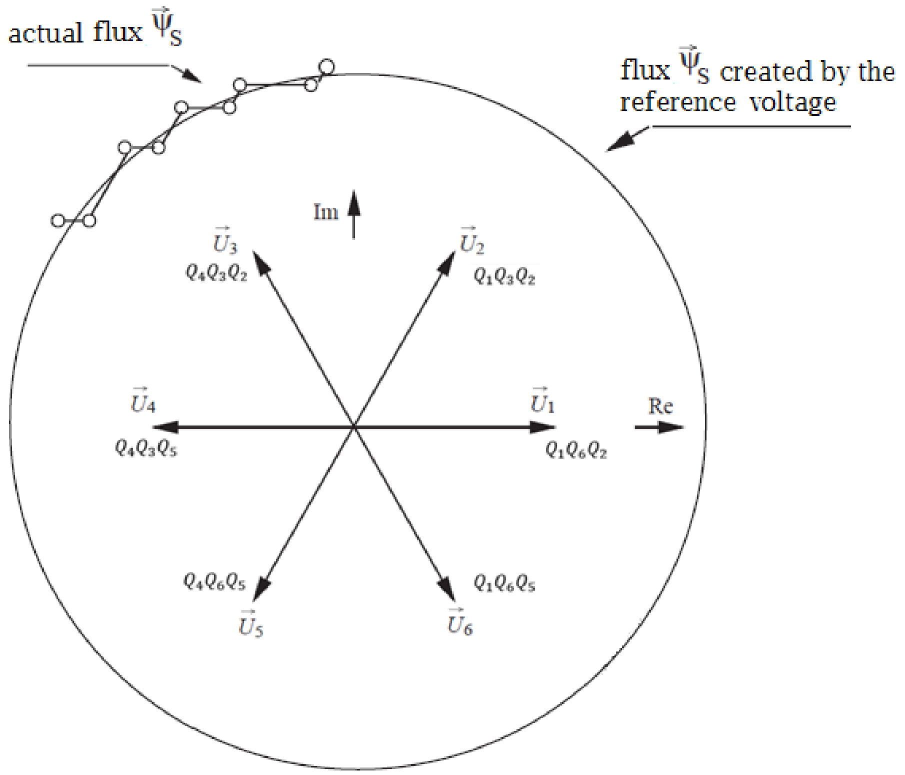

Figure 15: Space vectors of a three-phase bridge inverter, the reference stator flux trajectory and the actual stator flux (The small circles represent the zero voltages).

the converter causes significant switching losses. Therefore, the higher the used switching frequency is the higher the switching losses become. However, using higher switching frequency often results into easier filtering and therefore enables the use of smaller filter components which reduces the overall size of the converter. Other disadvantages of the IGBT converter are the machine bearing current problems and the machine terminal overvoltages due to high dv/dt. [29]

2.3.4 Electric Motor

An electric motor is an electrical machine that functions precisely the opposite to the electric generator. Electric motors transform electrical energy into mechanical energy. They can be divided into asynchronous motors and synchronous motors. Of these two types the asynchronous motors are the more commonly used motors in the industry. Their benefits are a simple design, mechanically strong structure and their convenience for direct on-line starting. However, their disadvantages are low efficiency of 0.8-0.86 and low overloading capacity at the field weakening area [30, p. 50]. In addition to this, the control of induction motors is more difficult because the rotor currents cannot be measured. The synchronous machine was introduced in 2.2.2 when it is operated as generator. The operation in the motor mode is similar but opposite to that of the generator mode. In this section, we will only discuss the asynchronous motors because that is the motor type that will be used in the DC power plant HIL model of this work.

Like a synchronous machine, an asynchronous machine also consists of two main components, the stator and the rotor. The stator is the stationary part that is usually made of laminated steel to reduce losses due to eddy currents. The stator is slotted and a three phase winding is inserted in the slots for producing a rotating magnetic field. The windings are supplied by a three phase voltage and they are connected either in star (y) or delta (Δ) depending on what kind of a starting method is used.

The rotor is the rotating part and it too has a multiphase winding in it. Two different types of rotors exist, the squirrel cage rotor and the slip ring rotor. According to these, the asynchronous machines can be divided into squirrel cage induction machines and slip ring induction machines. However, the majority of electrical motors in ships are squirrel caged induction motors [30, p. 51]. Between the stator and the rotor, a small air gap exists creating a magnetic circuit with the stator and the rotor. [12]

By inserting a three phase AC current into the stator windings, a rotating magnetic flux is formed. This rotating flux cuts the rotor windings and, according to Faradays law, induces an EMF on them. This creates currents in the rotor windings and, according to Lenz's law, the currents attempt to resist the rotation of the stator flux in respect to the rotor. This creates a torque on the rotor, forcing it to rotate in the same direction as the stator flux.

As the rotor speed keeps approaching the stator flux speed, the induced currents also decrease. If the rotor speed reaches the stator flux speed, the flux lines no longer cut the rotor windings and no current is induced anymore. Therefore, for the currents not to decrease to zero, the rotor has to rotate at a smaller speed than the stator flux. This difference in the speed between the stator flux and the rotor is called the slip speed s. Usually the slip is defined as a relative value, i.e.

$$s = \frac{n_s - n}{n_s}, \tag{25}$$

where n_s is the stator flux speed and the n is the rotor speed.

To describe the dynamic operation of the induction machine, the following equations [12] are used. In a coordinate rotating at arbitrary speed ω_k, the voltage equations are

$$\underline{u}_s = R_s \underline{i}_s + \frac{d\underline{\psi}_s}{dt} + j\omega_k \underline{\psi}_s \tag{26}$$

$$0 = R_r \underline{i}_r + \frac{d\underline{\psi}_r}{dt} + j(\omega_k - \omega_m)\underline{\psi}_r, \tag{27}$$

where subscript s means for stator, subscript r means for rotor, R is the resistance, i is the current, ψ is the magnetic flux linkage and ω_m is the rotor angular speed. The rotor voltage is here set to zero as is usually the case with squirrel cage induction machines because the rotor windings are short circuited. The flux linkage equations are

$$\underline{\psi}_s = L_s \underline{i}_s + L_m \underline{i}_r \tag{28}$$

$$\underline{\psi}_r = L_m \underline{i}_s + L_r \underline{i}_r, \tag{29}$$

where L_m is the mutual inductanse between the stator and the rotor. The stator and rotor inductances can also be expressed as

$$L_s = L_{\sigma s} + L_m \tag{30}$$

$$L_r = L_{\sigma r} + L_m, \tag{31}$$

where $L_{\sigma s}$ and $L_{\sigma r}$ are stator and rotor leakage inductances respectively. Using these equations, a dynamic mode equivalent circuit can be created as shown in Fig. 16.

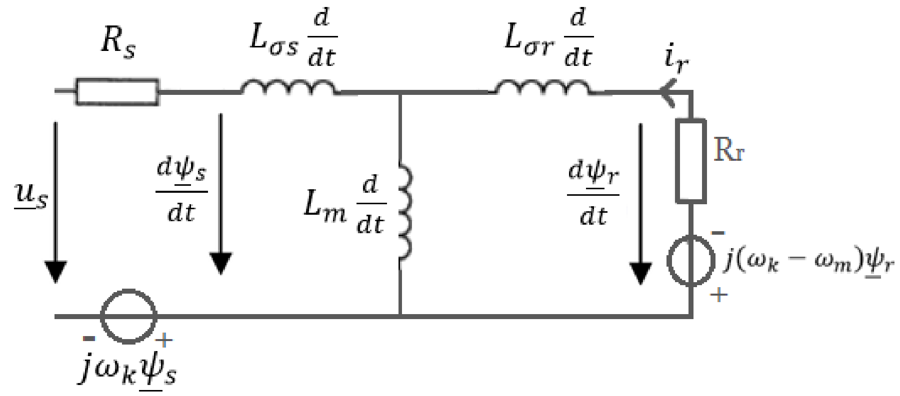

Figure 16: The dynamic mode equivalent circuit of the induction motor in a coordinate rotating at arbitrary speed ω_k.

In a general case, to take into account the mechanical aspects of the induction motor, the equation of motion is also needed together with the voltage and flux linkage equations. The equation of motion of the rotor is

$$\frac{d\omega_m}{dt} = \frac{p}{J}(T_e - T_L) \tag{32}$$

where J is the moment of inertia and T_L is the load torque. The electrical torque of the three phase machine is

$$T_e = \frac{3}{2} p Im\{\underline{\psi}_s^* \underline{i}_s\} \tag{33}$$

2.3.5 Power Transformer

A power transformer is an electromagnetic device that is mainly used to regulate the magnitude of a voltage into the level required by the system. In conventional marine power systems, transformers are used for different cases, e.g. as distribution transformers or propulsion transformers. In onboard power systems, there exist many different transformer designs in use but excluding small transformers, the most common type in ships is dry transformer with an air cooling [30].

In the DC power system HIL model of this work, transformers are mainly omitted and only used to separate the 400 V AC distribution system from the converters that supply them with three-phase AC power. A transformer steps down the converter output voltage to the required level for the AC grid and provides galvanic isolation between the AC grid and the DC grid. Other benefits of using a transformer between the converter and the grid are improved quality of the power inserted to the grid and also reduced common mode EMI and current distortion in the grid.

In its simplicity, a transformer consists of a laminated ferromagnetic core material and windings wrapped around it. The windings that receive power are called the primary windings and the windings that feed the output are called the secondary windings. When the primary is supplied with an AC voltage, the varying AC current in the primary windings creates a varying magnetic flux into the iron core. The core constitutes a closed path for the flux. The varying magnetic flux then induces an EMF on the secondary windings. The voltage on the secondary is given by

$$V_s = \frac{N_s}{N_p} V_p. \tag{34}$$

With three-phase power transformers, there exist three sets of primary and secondary windings. For both primary and secondary windings, three forms of connection are possible: star (Y), delta (Δ) and interconnected-star (Z). The operation of the transformer slightly differs depending on which connection is used. In star connection, the ends of the windings are connected to form a neutral point. This neutral point is usually an advantage as it enables the use of two voltages (phase and line voltage) which have a relation $\sqrt{3} : 1$ to each other. This connection is especially suitable for high voltages and moderate currents. In delta connection, the opposite ends of the windings are connected together to form a closed mesh or a Δ. The advantage of a delta connection is that the relation between the line current and the phase current is $\sqrt{3} : 1$. Additionally, the connection suppresses the third harmonic. Disadvantages are that it requires more copper and that since the line voltage is equal to the phase voltage, isolation is harder. The delta connection is generally used in the industry. The electrical features of the interconnected-star connection are basically the same as star connection. The advantage it has over star connection is that when the secondary is connected in interconnected-star, the primary can be a star connection without the risk of voltage unbalance. The interconnected-star connection is commonly used with small voltages and powers [31, p. 72]

2.3.6 AC Switchboards

Since the main distribution network of a DC power system on board a ship is DC, the main AC switchboard, including its generator and feeder current breakers, are omitted from the ship. However, since some loads, e.g. “400 V hotel load”, require AC power, the AC distribution system cannot completely be ignored. Therefore, on board the ship there also exists a small 400 V and 50 Hz AC distribution network that is fed with island converters and power transformers.

Using island converters, the AC distribution switchboard is connected to the power transformers through isolation switches. This enables disconnecting the switchboard from the DC bus in case of fault situations. E.g. if a short circuit occurs in the AC distribution switchboard, the switchboard is quickly disconnected from the DC bus and that way, the fault currents are blocked from entering the main DC bus. Also, like the main DC bus, the AC distribution switchboard too is divided into two parts using an AC CB. That way, in case of fault situations, the CB can be opened and half of the switchboard can be operated normally until the fault is cleared from the faulty side.

2.4 Propulsion Unit

The primary function of any marine plant is to convert the energy of the fuel into useful work that can be used for the propulsion of the ship. However, in the DC power system HIL model, we are not currently interested in the operation of a propulsor itself and therefore, only the propulsion motors will be modeled in the HIL model. The shaft power that the propulsor would normally require, will be inserted to the model from the simulator software. Nonetheless, this section will briefly introduce a common propulsion unit system to provide the reader with a general understanding of a marine power system.

The propellers can be divided into two groups of propellers, the fixed pitch propellers (FPP) and the controllable pitch propellers (CPP). In the FPP:s the position of the blades (and thereby the propeller pitch) is fixed and it cannot be changed in operation. In the CPP:s the hubs are relatively larger because the hub must have space for the hydraulically activated mechanism for pitch control of the blades. The disadvantage of the CPP:s is that they have a slightly lower efficiency due to their larger hub size. Of the two propeller types, the FPP:s are relatively cheaper and therefore, usually ships that do not require a particularly good maneuverability are equipped with an FPP.

Nowadays, some of the most common propulsion systems used in ships are ABB branded azimuthing podded propulsors called Azipod®. The Azipod propulsion system consists of the Azipod itself but also of frequency converters, transformers, switchboards, generators, automation, controls etc. The major advantage of an Azipod unit is that it can rotate freely 360° to give thrust in any direction. Therefore, the ship does not need any rudders, thrusters nor long shaft lines inside its hull.

The structure of an Azipod is shown in Fig. 17. In the Azipod model, the motor exists inside the pod and the propeller is directly connected to the shaft of the motor. Basically, the Azipod unit consists of four main modules; the propeller module, the electric motor module, the strut module and the power transmission and steering module [32].

The propeller module consists of an FPP which is driven at variable speed, both in ahead and astern rotation. The Azipod propellers are forward-mounted propellers. When driving in the ahead direction, the Azipod propeller is designed for the preferential use of the pulling propeller. For high pull requirements the Azipod is sometimes provided with a Nozzle. This option is usually meant for vessels that operate at lower speeds. In other cases, the propellers are mainly open propellers.

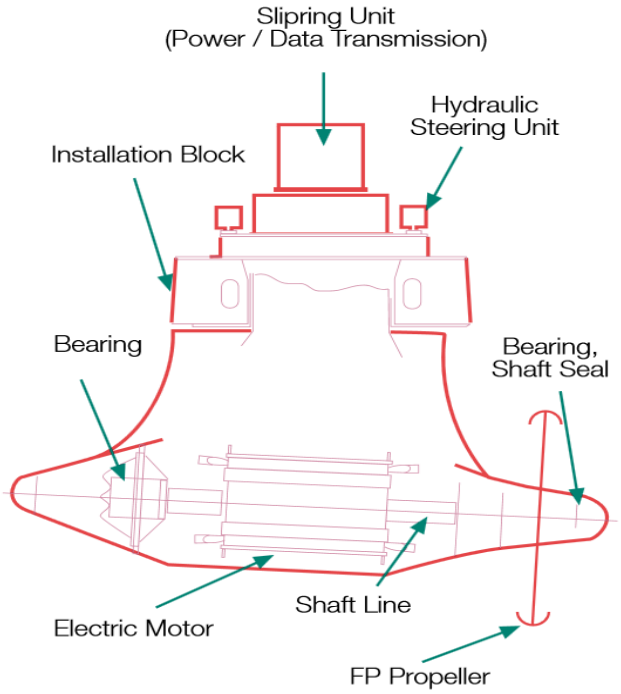

Figure 17: A crossectional view of the Azipod design with a fixed-pitch propeller. [32]

The electric motor module consists of the electric motor with an FPP that is mounted directly onto the motor shaft. The uniform frame design enables the motor to be directly cooled via the convection of the seawater. Therefore, this eliminates the need for a cooling system and problems related to it.

The strut module acts as a connective element for the Azipod structure and it contains the control cables together with the piping and power supply bus bars for the propulsion motor.

The power transmission and the steering module consists of either hydraulic or electric steering motors (usually 2-4) together with the control and equipment boxes. With these steering motors the Azipod can be turned to any position in 360 degrees. The position of Azipod can either change the position of the ships movement or keep it sailing straight ahead.

The benefits of the Azipod units are that they provide a high torque and a good lateral-directional thrust that improves the controllability of the vessel. The propeller can be turned in all directions which enables great maneuverability. The Azipod units also offer low fuel and oil consumption, a lower noise and vibrations than other conventional systems and extremely low emissions. However, the disadvantages of the Azipod units are higher initial capital cost and the requirement of relatively large number of diesel generators for producing the power. [33]

3 Control of Onboard DC Power System Components

3.1 Onboard Power Management System

In onboard power systems, there usually exist several power generating units and many power consuming units, of which the major ones are the propulsion units. Keeping the generated power slightly higher than the consumed power is essential for the operation of the system. Doing this efficiently, while also maintaining high safety and reliability on board a ship, requires an efficient power management system (PMS), especially for more complex diesel electric powered vessels. This section will introduce a few of the main functions and benefits of a PMS on board a ship. The interaction between the PMS and other control systems on the vessel and the operation of PMS in blackouts will be of high interest in the future testing with the HIL model.

The onboard PMS is an upper level automation system which is primarily built to maximize the performance of marine vessels and provide optimal and safe operation of the onboard power plant and diesel engines. It is a collection of control modules which handle the generation and consumption of power and interact with different control protection systems around the vessel. Some of the main functions of the PMS are e.g. load dependant start/stop and load sharing between the generating units. [34]

The load-dependent starting and stopping of the generator sets are based on a power available calculation of the PMS. In order to prevent a blackout, the onboard power system must always have a sufficient power capacity to satisfy the power consumption of the loads connected to the system. The minimum available power is therefore:

$$P_{min}(k) = \sum_{i=1}^{k} P_{gi} - P_{con}, \tag{35}$$

where P_{gi} is the sum of the power generated by all generators on-line and P_{con} is the total consumed load power, shared among generating sets. In AC power plants, the rotating speed of the diesel engines is synchronized to the frequency of the AC grid voltage. The generated power per generator is more or less constant and one way to vary the power generated to the system is to either decrease the number of on-line generators or increase it (in case there is enough capacity left for this). Therefore, calculating the power generating capacity of the system is easy as it can be done by simply calculating the number of on-line generators and knowing the power ratings of the generating sets [35]. In a DC power plant, the speed of the generators varies and therefore, the generated power does so too. This requires for an even more efficient PMS and increases the importance of efficient communication between PMS and various monitoring devices around the system. These monitoring devices should constantly calculate both the available power from the generators and the required power by the loads, and inform it to PMS. At varying loads, PMS then optimizes the generated power by controlling the speed of the diesel engines and that way optimizes the fuel consumption for maximum efficiency. In case of very small loads, PMS can also cut off the number of on-line generators like in AC power plants.

When running generators (or power sources in general) in parallel, controlling the distributed power between the generators is important. In AC power plants, both active and reactive power flow must be controlled. Active power is usually controlled by an engine governor and reactive power is controlled by a voltage regulator of the generator. However, since in a DC power plant no reactive power is generated to the main bus, only the active power generated by the generators must be controlled. A common method to control the active power is a voltage droop technique which will be discussed in 3.2. Controlling the load sharing between generators operating in parallel is important because otherwise one generator may become more burdened than wanted and the benefit of using several generators is lost. E.g., if the loadings of some generator sets vary too much from the wanted load points, they might deliver excessive currents which can result in greater thermal stresses on these generating units and thus cause a reduction in the system reliability. Any small difference between generator voltages will result in unbalanced load division or, in more severe cases, circulating current.

3.1.1 Blackout Prevention and Recovery

The term blackout is used when there occurs a total loss of electric power generation in a ship. Sometimes, the term partial blackout is also used to describe a situation where the power supply is lost to part of the electric distribution system. Due to a blackout, it then follows that the capability for propulsion and station keeping is also lost. Although a blackout is not a common condition and it rarely occurs, they are often high safety risks and avoiding them is highly desired. Therefore, preventing them and recovering from them is very important for the safe operation of a ship.

Usually, in a ship there can be several reasons that can cause power failures resulting to a blackout. However, the main reasons are usually faults in the main machines and engines. A lot of contribution is made for preventing these faults. E.g. an engine governor fault can lead to a high amount of fuel flowing into a faulty engine which in turn can cause reverse power tripping of paralleled engines. This can be often prevented by monitoring the engine and opening bus-tie breakers for isolating the faulty engine from the rest of the grid. Similarly, a generator voltage regulator fault can lead to an over excitation of a faulty generator and cause the under excitation trip of paralleled generators. This can also often be prevented by monitoring the generator and opening bus-tie breakers for isolating the faulty generator from the rest of the grid. Other common faults, with the risk of causing a blackout, are operation faults, short circuits and voltage and frequency transients. Operation faults can cause opening/closing the wrong breakers or choosing wrong operation modes for certain applications and thus result into a serious fault. Short circuits often cause voltage drops in the grid and can cause tripping of motors. The transients can cause dangerous inrushes in the grid. Both the risks created by short circuits and the transients can be prevented by opening the bus-tie breakers (or with more careful designing) and the risks from operation faults can be prevented by keeping operation simple and consistent. [36]

Although much contribution is made for preventing complete or partial blackouts, it is often safe to say that no system is 100 % sure and therefore, there is always a possibility for a blackout. Therefore, the automation system of a ship must also be designed for recovering from blackouts. The restoration sequence is usually controlled by the PMS. It starts by first attempting to start the available generator sets and synchronizes them to the rectifiers. After this, the PMS configures the system for the right operational mode. The blackout recovery in a DC power plant is often faster than in the conventional AC power plants because there exists no need to synchronize the speed of the diesel engines to the bus voltage frequency (bus voltage frequency is 0 Hz). Therefore, the generators can be connected to the grid very quickly after a start up.

3.2 Control of Generator Drives

A synchronous generator together with its prime mover (usually a diesel motor) and their control systems are shown in Fig. 18. The figure consists of a diesel motor with a speed controller (a speed governor), a synchronous generator with an excitation system and an automatic voltage regulator (AVR) and a power rectifier with a rectifier control system. This section will discuss the speed governor of a diesel engine and the voltage regulation of a synchronous generator. In the DC power plant HIL model, the power rectifier (a thyristor bridge or a diode bridge) is mainly used as a diode bridge to only rectify the AC power and not to regulate the output voltage. Therefore, the control of a power rectifier will not be discussed in this section. However, control of load sharing between parallel converters using a voltage droop technique will be introduced.

3.2.1 A Speed Governor

The rotation speed of the diesel engine is basically controlled by controlling the amount of fuel injected into the cylinders of the engine. The speed governor of the diesel engine is usually implemented with a PID-controller (Proportional–Integral–Derivative) that is given a speed reference from which it adjusts the injected fuel into the engine. The actuator then transforms the electronic output signal of the speed governor into mechanical control movement.

In more conventional ships with AC based distribution systems, the rotational speed of a prime mover is kept constant at a speed of 3600 $\frac{r}{min}$ $(60Hz)$. However, the DC power plant only requires the generators to match system voltage because, due to the DC distribution system, the frequency at which the generators are run becomes insignificant. Therefore, the speed of the prime mover can be dynamically optimized to the system load situation for maximum performance. At lower loads, the speed of the prime mover can be decreased and at higher loads it can be decreased. This results immediately into reduced fuel consumptions compared to the conventional AC systems. Other significant benefits of using the generators at variable speeds are

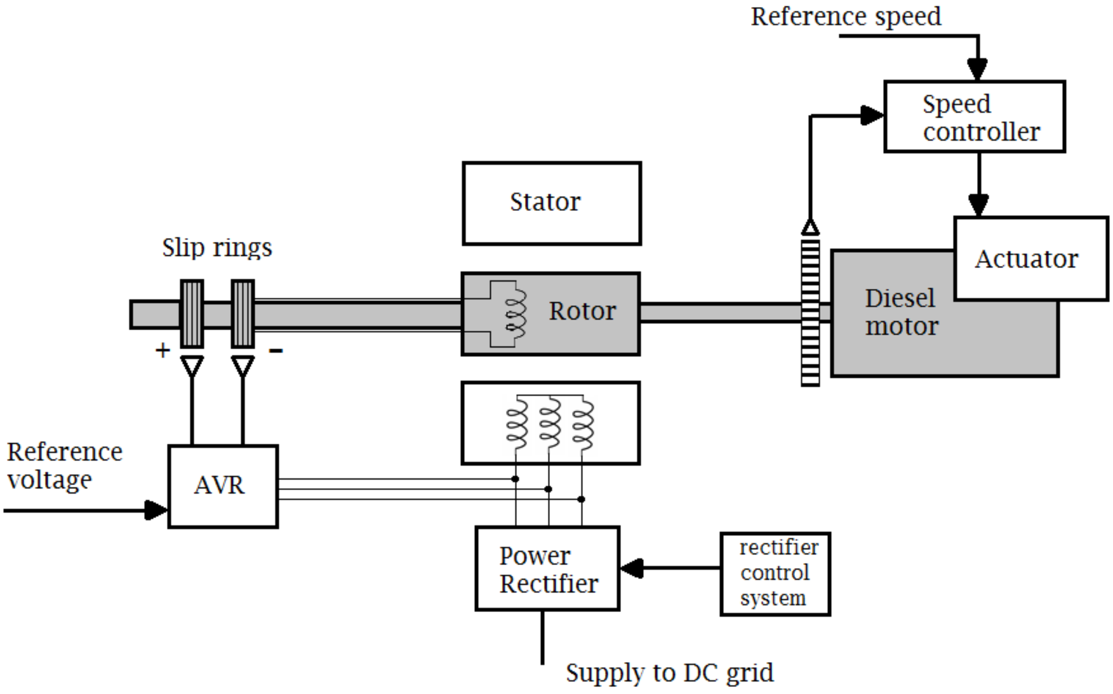

Figure 18: A diesel engine with a speed control system, a synchronous generator with an AVR and a power rectifier with a control system. [30, p. 33].

reduced green house gas emissions due to lower fuel consumption, reduced nitrogen oxides, NOx, emissions and urea consumption, potential reduction in audible noise level and reduced maintenance costs due to reduced wear and tear on the engine.

3.2.2 Generator Voltage Control

In subsection 2.2.2, the construction and dynamic modeling of a synchronous generator was briefly introduced. It was mentioned that to produce the required rotating magnetic flux, the field winding needs to be supplied with a DC current. Therefore, to work the generator requires an additional power source (an excitation system), which is controlled by a voltage regulator, to produce the field winding. Basically, the excitation systems can be classified in either rotating or static excitation systems.

In the rotating excitation systems, the field current is produced by a DC current machine or an AC current machine with a rotary rectifier (usually diodes). However, in larger generators the required field current is large and therefore, commutation problems with the DC machines occur. In addition to this, the DC machines may cause the dynamic properties of the exciter to deteriorate in some cases. Therefore, nowadays the rotating exciters are mostly built with AC machines which are simpler and more reliable than DC machines. The benefit of using a rotating excitation system is that the DC current is fed directly, without slip rings, to the field windings of the main machine which results into less need for maintenance. A disadvantage, however, is that the exciter response is limited by the exciter machine time constant.

[14, p. 22]

The static excitation is performed by taking the power supply to the excitation system directly form the generator terminals and transformed into DC current which is then fed to the rotor windings using slip rings. In this system the field current usually flows through an excitation transformer, a power converter and a field current breaker. The transformer regulates the generator terminal voltage to the required input voltage of the converter, provides galvanic isolation for the field winging and the machine terminals and acts as a commutation reactance for the converter. The converter is usually a controlled power rectifier that rectifies the current into a controlled DC current. The field current breaker is used to break the field current and discharge the energy from the field windings into a discharge resistor as fast as possible. The main advantage of the static excitation systems is their relatively fast reaction to control signals which also makes them more reliable. A disadvantage of the static excitation system is the need of slip rings which require more maintenance. Nonetheless, static excitation systems are becoming the main source of excitation for high power generators. [14, p. 23]

An AVR is a device designed to automatically regulate the terminal voltage of a synchronous generator. The AVR is used to control the amount of current supplied by the exciter and that way control the terminal voltage of a synchronous generator. Nowadays, common AVR types are microprocessor based control systems that regulate the terminal voltage of the synchronous machines by directly controlling the field current. To achieve this, it uses fast switching semiconductor technology.

A block diagram of a generator drive with a general excitation and AVR system is shown in Fig. 19. In this system a measuring element constantly measures the terminal voltage V_g of the generator and feeds it into a comparator. This comparator compares it to the reference voltage V_{ref} and produces a voltage error signal ΔV. The error signal is then amplified and fed into the exciter whose output (the field current of the generator) is altered so that the voltage error is minimized. The process is stabilized using a negative feedback loop. Also, to protect the AVR, exciter and the generator from excessive voltages and currents, several limiters are usually used. They make sure that the signals stay between preset limits. [12, p. 23]

A disadvantage of the AVR is, however, that in transient states of the generator, the AVR might have a negative impact on the damping of power swings. As these power swings cause the terminal voltage to oscillate, the AVR attempts to decrease the voltage oscillation by changing the field current which, in some cases, might oppose the rotor damping currents which are induced when the rotor deviates from the synchronous speed. Therefore, to dampen these swings in the power system, a power system stabilizer (PSS) is often used with the AVR. The PSS detects the fluctuations in the terminal power and provides an additional signal into the control loop to compensate for the voltage oscillation. [12, p. 23]

3.2.3 Converter Load Power Sharing

Using several smaller generating units in a power plant offers many advantages compared to a situation where only a single high-power generating unit is used. The

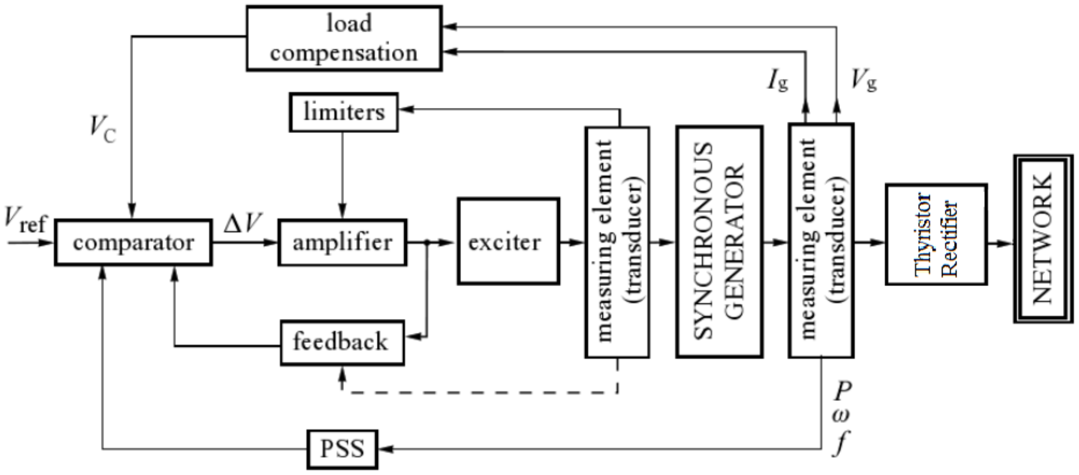

Figure 19: A block diagram of a generator drive with an excitation and AVR system [13, p. 23].

system with more generators is more reliable because should one of the generators break, not all power capacity is lost. The efficiency of the power plant also increases considerably when the generators are run at their rated capacity. At lower loads, this would be considerably harder with only a single generator, even if the generator could be run with variable speeds. Running several generators in parallel also increases the safety of the system, especially in cases of maintenance and repair. In theses cases the generator which requires attention can be cut off and isolated from the rest of the system without disturbing the operation of the system. Due to these reasons, generally all maritime vessels employ at least two generators for power generation.

As was mentioned in 3.1, in marine vessels employing DC power systems, no reactive power is distributed to the main DC bus. Therefore, in a DC power plant, only the active power must be controlled. This is achieved by controlling the load sharing of the converters connected to the DC bus in such a way that each converter share the load current equally. In this section, we will briefly introduce a voltage droop technique which will be the main load sharing method tested in the HIL model of this work.

A voltage droop [37] is a control method which is used to maintain the current shared between the generator converters consistent. A traditional droop control is illustrated in Fig. 20. Each converter connected to the DC bus has a current dependent voltage drop due to commutation overlap and therefore, especially in constant firing angle mode, the converter can be modeled as a DC voltage source connected to the DC bus through a resistance. Using a droop controller, the converter output voltage is reduced when the supplied current increases. Usually, the droop for large generator converters is small and it takes a rather large current deviation to change the bus voltage level significantly. This results to a relatively constant DC bus voltage which is highly desired for efficient operation. The voltage droop method is a simple method to promote current sharing between paralleled converters connected to the DC bus, without the need for a central control.

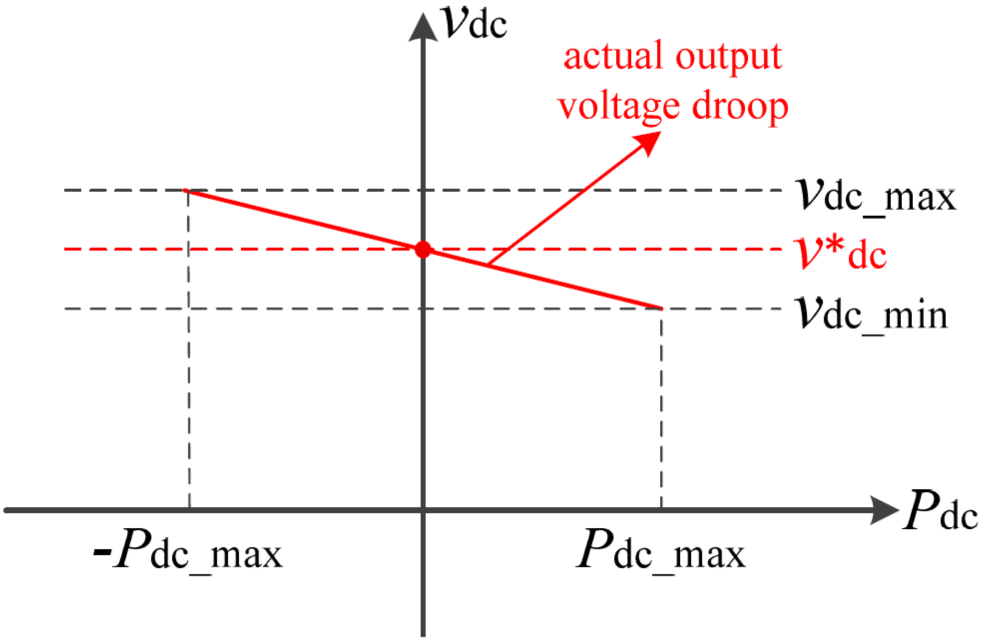

Figure 20: Voltage droop control diagram at the DC side. [38].

Implementing a voltage droop technique for load sharing of generating units offers several advantages. This method requires no communication between the converters and therefore no wiring is needed between them. Voltage droop method is also rather simple to implement and it is easy to expand the paralleling system. In addition to this, the method is highly reliable during large disturbances such as failures or disconnection of a generating unit. A disadvantage of the voltage droop method is that if the power ratings of the paralleled generator converters are too different, the current sharing becomes more difficult. Also, with this technique, the deviation of the DC bus voltage becomes inevitable. [39]

3.3 Operational Optimization With a DC Power Plant

DC power systems on board enable many new ways for optimizing the operation of the ship in different situations. E.g. in dynamic positioned (DP) offshore vessels, the electric thruster loads are normally low because of low propeller speeds in normal weather conditions and the power produced by the generators is higher than required for safety reasons. Therefore, to optimize the fuel consumption efficiently, lowering the amount of generated power is important. In some sever DP operations, the power plant is operated in split mode operation where basically the number of on-line generators is varied depending on the need. However, since a total optimization of running engines is not possible in this mode, it does not utilize the full benefits of electric propulsion. With an onboard DC power system, the speed of the engines can be adjusted to the required load without varying the number of generators on-line. Therefore, compared to AC power systems, a DC power system offers more possibilities in situations like DP operation which require split mode operation of the system. [3]

Unlike the conventional AC power systems, a DC power system provides a flexible system for combining different energy sources like turbines, fuel cells, photovoltaic cells, energy storages etc.. To have a smart and efficient power system with some or all of these different power sources, utilizing a functional energy management system (EMS) is required. Since different energy storages have certain unique characteristics which may in many cases complement each other, using them with a smart energy managements system could provide a hybrid energy storage system on board. E.g. since the charging and discharging times of super capacitors are relatively short, they can be used to supply high amount of power for a short duration of time. On the other hand, fuel cells can be used to provide huge amount of energy during high load demands. The important function of the energy storage system here would be to decide which storage system to be used in which situation. Another potential benefit of an energy management system in the future could be the ability to e.g. take into account varying fuel prices and availability of different fuel and optimize the consumption based on this information. [40]

3.4 Control of Motor Drives

To obtain effective propulsion on board a ship, it is important to accurately and efficiently control the torque and speed of the propulsion motors of the vessel. The ship propellers (usually FPP:s) are directly mounted on the shafts of the motors. Therefore, depending on the wanted movement speed for the ship and the loading caused by the water flow, it is important to efficiently control the motors rotating the propellers. This enables good energy efficiency and maneuverability of the ship.

The first thing that has to be done before starting moving the ship, is turning on the propeller motors. In 2.3.4, it was mentioned that an advantage of the induction motor is the convenience of starting it by directly connecting it on line. The benefit of the direct on line starting is it being the simplest and cheapest starting method. However, when starting an induction motor, the motor draws a large amount of current which can be even up to eight times the nominal current and attenuates only after the motor speed reaches 80 % of the nominal speed [12, p. 153]. To prevent this starting current from damaging the stator windings, several starting methods exist that can be used for limiting the high current.

One starting method that is often used with small and medium sized motors is the star-delta method. In it, the stator windings are connected in delta (Δ) on normal operation and in star (Y) when starting the motor. When the motor is being started, the stator windings are connected in a star (Y) connection. In this case, the voltage on the stator windings decreases and thus decreasing the starting current too. In a star connection, both the current and the torque are only 30 % compared to those values in a delta (Δ) connection. Therefore, the starting current decreases significantly. After the motor speed exceeds 80 % of its nominal speed, the stator windings are connected in delta (Δ) which is the normal mode of operation. [41]

Although the star-delta switching offers smaller starting current and reduced transients, it is often not the best solution due to it causing a high current inrush and a reduction in torque when changing the connection. Another starting method, where soft starters are used, has shown to often offer better results. A soft starter can basically be two antiparallel thyristors connected in series with the stator windings. The soft starter enables to gradually control the RMS value of the terminal voltage by controlling the firing angle of the thyristors. By temporarily reducing the motor terminal voltage at the starting, the high current inrush can be reduced and the shaft torque can be limited. The use of soft starters to reduce the voltage at starting of the motor helps protecting the equipment from damage and also provides more more gradual ramp up to full speed. [12, p. 156]

After the machine is started, the speed of the machine is varied depending on the required application. The rotational speed of the machine is

$$n = (1 - s)\frac{f}{p}, \tag{36}$$

where s is the slip, f is the stator frequency and p is the number of pole pairs. As can be seen from (36), the speed can be controlled by controlling either the slip, the frequency or the number of pole pairs. Of these methods, the control of the supply frequency with a frequency converter is proven to be the best method in terms of losses, control accuracy and dynamics [12, p. 162]. The most common frequency converter type is a PWM based voltage source converter discussed in 2.3.3.

For controlling the speed of the induction machine in normal operation, many different control schemes have been developed over time. Some more commonly known methods are the scalar control, vector control, flux control, adaptive control and the direct torque and flux control (DTC). Of these control methods arguably the most efficient control method is the DTC which will also be the main method used to control the motor drives in the HIL model of this work. Therefore, only the DTC will be discussed in this text.

The DTC used in motor drives of the HIL model of this work is a space vector PWM based control scheme that effectively merges field orientation, current control, and PWM in one. Therefore, the DTC controls the IGBT inverter and the motor as a complete system. All switch changes of the inverter are based on the electromagnetic state of the motor. It is very efficient but also computationally intensive with a sample interval of up to 25 μs [42].

A block diagram describing the DTC of the motor drive is illustrated in Fig. 21. The speed of the induction motor is either estimated or measured using e.g. a speed sensor. The speed is then compared (e.g. with a PI-controller) to the reference speed and from the comparison, a reference torque is obtained. Based on the reference torque T_{ref} and the torque estimate $\hat{T}_e$, the output of the two-point controller d_T is obtained. Similarly, based on the reference flux linkage $\psi_{s,ref}$ and the flux linkage estimate $\hat{\psi}_s$, the output of the two-point controller d_ψ is obtained. Based on these two outputs of the two-point controllers and the flux linkage angle estimate $\hat{\theta}_{\psi s}$, the controller knows in which direction and how much should the flux linkage space vector be changed. The output d_T determines the angle of the flux linkage vector and the output d_ψ determines the length of the flux linkage vector. [12, p. 173].

To obtain the needed estimates for the control, the torque, speed and flux estimators are used. sometimes, however, the speed of the rotor is actually measured by using rotation sensors in which case there is no need to estimate the speed and instead the actual speed can be used. One way to estimate the mentioned quantities is by using the voltage model discussed in 2.3.4. The flux can be estimated from the voltage equation in the stator coordinates (Eq. 26) by rearranging it and integrating it:

$$\underline{\hat{\psi}}_s^s = \int_0^t (\underline{u}_s^s - R_s \underline{i}_s^s) dt. \tag{37}$$

Notice that in stator coordinates the speed in Eq. 26 is $\omega_k = 0$. Therefore, since voltage and current are known, the only quantity needed to be solved is the resistance which can be measured by supplying DC current into the stator windings and measuring the voltage drop. However, the temperature rise of the machine causes the resistance to change and therefore it is required to somehow estimate resistance too. The torque is estimated from the torque equation [12, p. 132] by inserting the flux linkage estimate in it:

$$\hat{T}_e = \frac{3}{2} p Im\{\underline{\hat{\psi}}_s^{s^*} \underline{i}_s^s\}. \tag{38}$$

The advantages of the DTC are a fast and flexible control of the induction motor. The torque rise time is also very short and the DTC enables several different control functions to be realized. The starting of the induction machine can be done very quickly in any electromechanical state of the motor. The DTC model also enables automatic optimization of the magnetizing level to the load which significantly improves the efficiency of the motor drive. [42]

3.5 Control of Island Converters

Like the AC motors, the 400 VAC distribution switchboard is connected to the DC bus through a power inverter which is used to transform the DC power from the bus to AC power for AC distribution. This small AC grid is called an islanded power system. Since the unbalanced loads and the harmonics drawn by non-linear loads cause grid voltage distortion, the island converters are specifically designed to enhance the quality of voltages. To be able to feed the relatively cleaner power for the AC distribution switchboard, the island converters require some additions and modifications in the control compared to the propulsion supply converters. The island converters that are used in the HIL model of this work are IGBT supply modules equipped with RLC-filters.

The typical switching frequency of 2-15 kHz in PWM-inverters causes high-order harmonics that might disturb some of the more sensitive loads in the AC grid and also increase the losses in the grid. To avoid these problems, the inverter is equipped

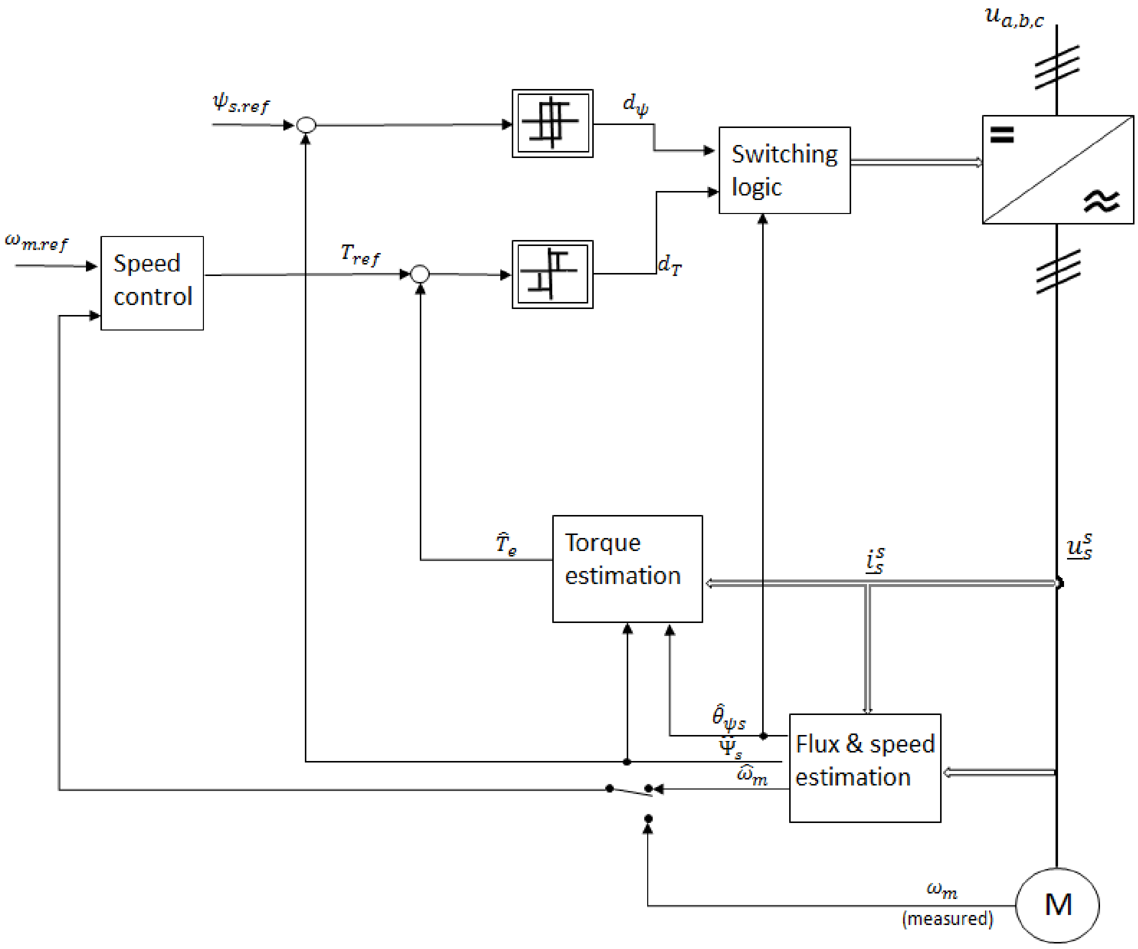

Figure 21: A block diagram describing the direct torque control. [12, p. 173].

with an RLC filter whose main purpose is to reduce the higher order harmonics produced by the inverter and smoothen the current fed to the AC grid. Often, a simple series inductor L would also be enough for the task. However, in higher power applications the size and cost of the filter increases significantly and also the dynamic response of the system might slow down. Both these issues, however, can be overcome by using a higher order filter.

Between the AC grid and the island converter, there also exists a power transformer that is used to step down the voltage for the 400 VAC distribution. Usually, these transformers have a delta (D) connected primary and a star (y) connected secondary with a neutral point connector (n). This connection is called the Dyn connection. The use of Dyn connected transformer is essential because it allows three-phase five-wire systems to be supplied with the converter. Other benefits of using a transformer between the grid and the converter is that, like the RLC-filter, the transformer also improves the quality of the power and reduces common mode EMI and current distortion in the grid. In addition to this, the transformer also provides a galvanic isolation between the AC grid and the DC grid.

A simplified block diagram of controlling an island converter with an RLC-filter and a transformer is shown in Fig. 22. The primary task of the control is to keep the AC grid voltage the same as the reference voltage and to limit the island current so it would not exceed the maximum allowed current. That way, the converter is also protected against overcurrent tripping.

The control scheme presented here is based on an island converter control presented in [43, p. 61]. In this control scheme, a Cartesian frame of coordinates (XY-frame) is used where the angular velocity of the frame equals the angular frequency of the grid voltage phasor:

$$\omega(t) = \frac{d\rho}{dt} = \frac{d\theta_g}{dt} = \omega_g(t). \tag{39}$$

In this control scheme, the voltage and current are measured using auxiliary measuring devices and transformed from the abc frame to the XY frame for feedback and feedforward signals. In the latter stage of the control, the signals are transformed back to the abc frame for producing the modulation signals. The modulation technique employed for converter control is the space vector PWM technique introduced in 2.3.3.

When expressing the converter output current and AC grid voltage (or more precisely, transformer primary voltage) in the XY-coordinate, they become

$$\hat{I}_t = I_{tX} + jI_{tY}, \tag{40}$$

$$\hat{V}_g = V_{gX} + jV_{gY}. \tag{41}$$

That way the AC side of the island converter system can be presented in the XY-coordinates:

$$L\frac{dI_{tX}}{dt} = -RI_{tX} + L\omega I_{tY} + V_{tX} - V_{gX} \tag{42}$$

$$L\frac{dI_{tY}}{dt} = -RI_{tY} - L\omega I_{tX} + V_{tY} - V_{gY} \tag{43}$$

In the system of Fig. 22, the control objective is to regulate I_{tX} and I_{tY} at setpoints I^*_{tX} and I^*_{tY} respectively by controlling inputs V_{gX} and V_{gY}. Basically, the control scheme can be thought to consist of two sub-controllers, X- and Y-axis controllers. For both of these controllers a compensator, $K_i(s)$ is used to process an error signal $e = I^*_{ti} - I_{ti}$ and generate a control signal u_i (i=X, Y). The desired AC-side terminal voltage V^*_{ti} is then obtained by supplementing the control signal u_i with control signals $\omega L I_{ti}$ and V_{gi}. Finally, the modulating signals m_x and m_y are produced by dividing the respective AC terminal voltage components V^*_{tX} and V^*_{tY} by the measured gain of the island converter, $V_{dc}/2$. The function of the Phased-Locked Loop (PLL) and a more detailed description of this control scheme can be found in [43, p. 61].

The control characteristics of the island converter depend largely on the DC-link voltage. As the load on the AC grid side increases, higher voltage drop occurs in the RLC-filter. Therefore, to maintain the load voltage at its reference, the magnitude of the converter output voltage is different depending on the loading. Therefore, it is important to keep the DC link voltage high enough for the operation.

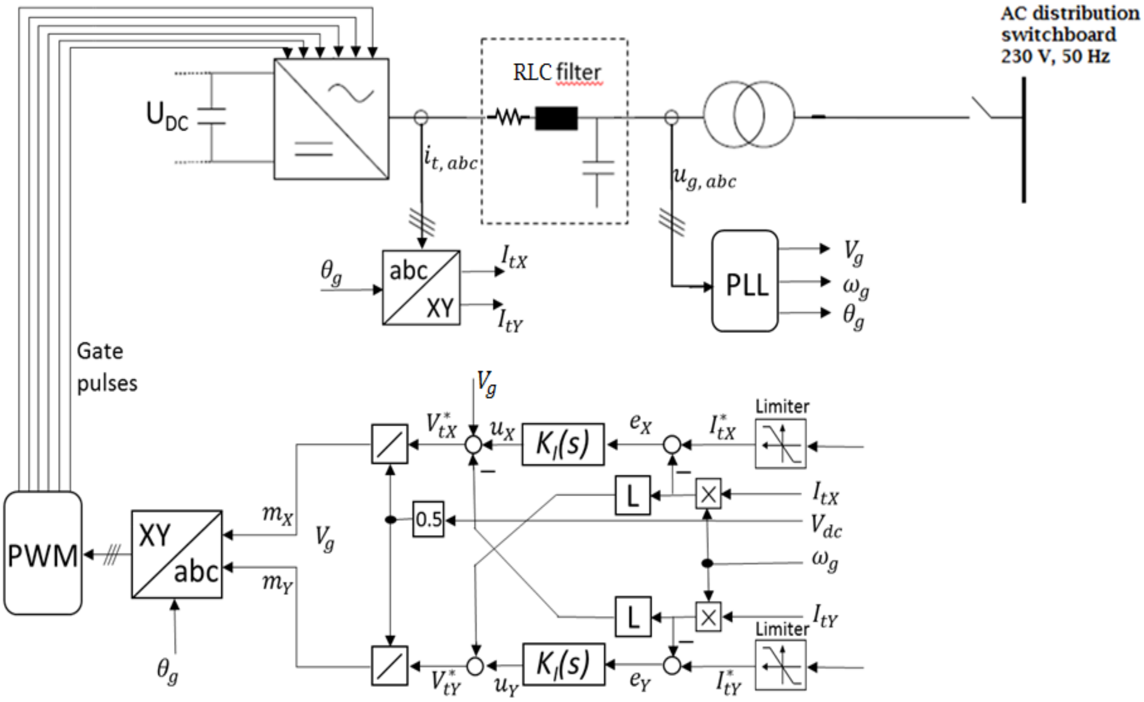

Figure 22: A simplified single line block diagram of the island mode converter current control scheme. The figure is edited from the figure in [43, p. 62].

4 Simulation Setup for HIL Testing

Testing the behaviour of a complete system and its components is an important matter as it enables the designer to know whether the designed system meets the preset functional requirements or not. Two main types of testing are usually the testing of a newly installed system and the routine tests made for maintenance and ongoing assessment. Both tests are important and required to ensure secure and efficient operation of the system.

Chapter 3 discussed the importance that the PMS and the power electronic control systems have regarding the control and protection of the marine power system and its components. Often, when designing power electronic controllers, the designers use simplified models in the early stages of the system design. This enables the designers to focus only on the design of the controller but it also overlooks the overall complexity of the system where the controller will eventually be inserted for operation. When inserting the controller to operate with the rest of the system, it must also be able to communicate with other devices in the system. Some complications, e.g. communication time delays between the different controllers, may often be encountered in the real system and therefore efficient testing is required.

Testing a complex system, e.g. a power system on board a ship, has several disadvantages. Building the whole system for testing is often expensive and time consuming. The test itself might also be very expensive depending on the complexity of the system. E.g. testing a power system on board often requires the tests to be made on the vessel. The cost of doing tests on board a ship is often high, especially if the ship happens to be at sea during the discovery of the fault. Repeating a test like this is very challenging and it is usually not possible or not recommended to test the limits of the system. One of the disadvantages is that some expensive components of the system might get damaged.

To overcome some of the disadvantages of testing the real system, the designers nowadays perform simplified simulations to obtain some initial information of the system operation. In a complete simulation of the system, the whole system is virtually modeled using a simulator software. The biggest advantage of such a model is naturally the less expensive price and the possibility to perform the tests in short time. In addition to this, there is no danger for the personnel working around the system nor for the components of the system. Another advantage is also the possibility to obtain very detailed results from simulations that could not be achieved in practice by measuring with the current level of technology.

The major disadvantage of the simulation testing is that it usually consists of too many simplifications that can make the simulation unreliable in real life. Building a good model requires expertise and thorough understanding of the simulated systems or otherwise the model will become prone to errors. These simulation errors can form a threat in the use of the machine. Therefore, it is often required that the simulation results are also verified with practical experiments.

According to the reasons mentioned above, system testing is very important, especially in the development stage of a system. However, testing the system by using real hardware can become expensive and has several disadvantages, e.g. be very time consuming. On the other hand, testing the system by building a virtual simulation model is cheap but it does not efficiently replicate the real operational conditions and thus it cannot be totally relied in the simulation results. To overcome most of these problems, the logical thing to do here would be to use a testing environment that is something in between the two above mentioned methods. In the following sections, a model which is part hardware and part virtual simulation will be introduced and some of the main requirements for building such a model will be explained. In this text, the focus will be on power electronics applications.

4.1 Hardware-In-The-Loop

HIL simulation is a real-time simulation technique which can be used to model and simulate complex machines and systems. In this technique, a real-time simulator is used to model a complete system or only a part of a system. The main components with their control algorithms are connected to the HIL simulator through hardwired I/O and fieldbus communication, and together these form a simulation loop which can be used to test the operation of a system in both normal and fault situations. This provides the tester a relatively inexpensive testing environment while also providing access to the hardware features that would not otherwise be available in a completely software based simulation model. Since the process itself is a virtually simulated model and only the intelligent devices are real, it offers several advantages which will be discussed in this section.

The idea of the HIL simulation is illustrated in Fig. 23. Basically, to produce HIL simulation, three hardware parts are required: A real-time simulator (processor), a development hardware (e.g. a desktop computer) and electronic control units (ECU). The simulator is the most crucial part of the HIL simulation. Therefore, it must be very powerful. It is where the software representation of the physical plant consists and which performs the calculations required for the real-time simulation. The simulator used in this work has a sample rate as low as 1-2 ns. This is seen as a highly sufficient sampling time because the fastest control logic performed in this work has a sampling time of 10 μs. The controller hardware consists of all the equipment to be tested in the model. In this HIL model, the controller hardware initially consists of only rectifier controllers, AVRs and protection relays. Eventually, the model will be expanded and more controllers will be used. The development hardware is basically the human machine interface (HMI) used to control the simulation. Usually, this can be a desktop computer or something similar. The development hardware contains e.g. the schematic editor in which the user can built different software models for the simulation. All the simulation results and real-time calculations can be seen in this hardware.

In Chapter 3, various control schemes in a DC power system were discussed. The main purpose of the HIL simulation in this work is to provide an environment to test these control schemes and different blackout prevention and recovery functions. To test these functionalities, only the power electronic converter controllers (basically, an AVR also consists of a power electronic converter controller) and protection relays are required as real hardware. To produce measuring responses as required by these

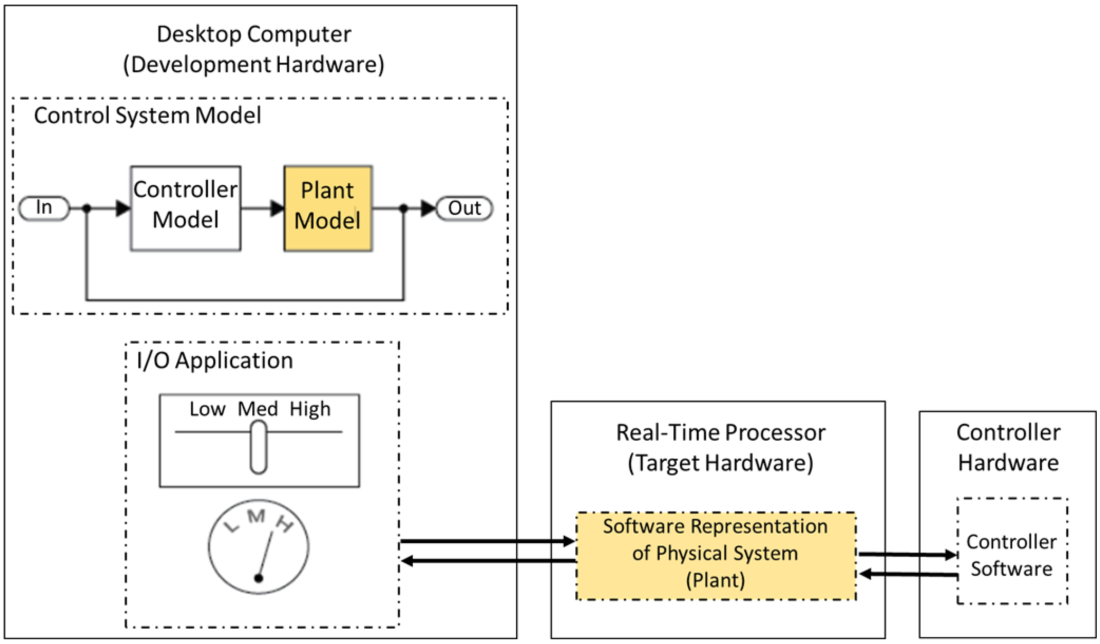

Figure 23: A description of the real-time HIL simulation. It consists of three hardware parts: the real-time simulator, the development hardware and the electronic control units. [44]

devices, the simulation also requires the use of current and voltage amplifiers that can generate and absorb small power high voltage/current signals. The HIL simulation performed in this work is sometimes also called controller HIL (CHIL) simulation [45] but in this text we will refer to it generally as HIL.

The real-time HIL simulation technique offers several advantages which are usually of interest to many different parties in the industry. The engineers want to test the controllers with non-ideal behavior, with different points of operation and in different fault situations. The managements usually want to increase the test coverage, decrease the costs of testing and accelerate the time to market of a product. All this can often be achieved with HIL testing because it enables detecting errors at earlier stages of the design and therefore enable quicker transition of technology from the experimental product phase.

The cost and efficiency of the HIL simulation, compared to the two other testing methods mentioned above, is illustrated in Fig. 24. The relations between the simulation models in the figure are not directly comparable to the practical situations because the cost and efficiency of the models naturally depends on many factors, e.g. the size and complexity of the system or, in case of HIL simulation, the amount of hardware to be tested. However, the charts in Fig. 24 do give a good perspective on the price/efficiency relationship of using these different testing methods. As can be seen from the figure, the HIL simulation offers significantly less expensive testing environment than testing a complete system and is significantly more efficient than purely software based simulations.

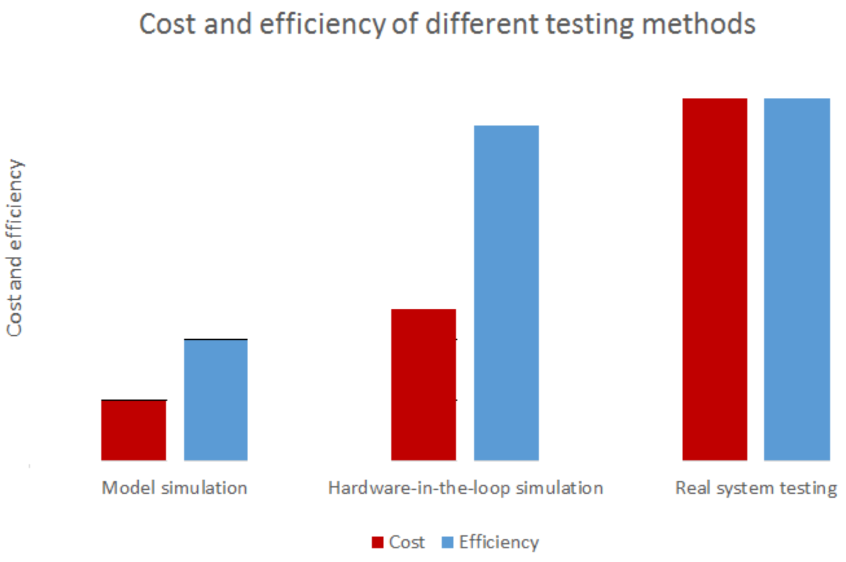

Figure 24: A cost and efficiency comparison between different simulation models. The relations between the simulation techniques are not directly comparable to practice but they do give a good perspective on the price/efficiency relationship.

In addition to the cost benefits, HIL testing environment offers several other advantages. Firstly, since the HIL models require less hardware than fully physical prototypes, building a HIL model is significantly faster than building a complete real model. Therefore, controller prototypes can be rapidly built and evaluated in the loop. Secondly, the controllers that normally operate in highly variable environments can be tested in controlled settings through HIL simulation which increases the repeatability of the test. Thirdly, the fidelity levels achieved with the HIL simulator are much higher than can be achieved by purely virtually simulating controllers whose dynamics or other attributes are not completely understood. [46]

The most challenging part of the HIL simulation is arguably the difficulty to attain acceptable accuracy with an achievable simulation time. The power electronic converters, especially IGBT inverters, can theoretically have high switching frequencies of up to tens of kilohertz. To obtain an acceptable accuracy for the model, the simulator must be able to produce a high enough processing power and a tiny enough sample interval. In the HIL model of this work, the switching of the IGBTs of the inverters are the components requiring the smallest sample intervals which can range down to tens of micro seconds. This will not, however, be a problem in this work because the CPU power of the HIL simulator is large enough for simulating the model designed in this work.

4.2 Communication Protocols

In its simplest, communication refers to a situation where a message is transmitted from source A to destination B. Basically the source generates a data after which a transmitter is used to convert the data into transmittable signals. A transmission system is then used to transmit this data to a receiver in the destination. The receiver converts the received signals back into data for the destination. The most commonly used transmission system between controllers in the HIL model of this work, is Ethernet network.

Ethernet is a widely used local area network (LAN) technology where multiple computers (or in our case, controllers) are attached to each other using a single cable. In this network, any controller can send a message down the cable and receive a copy of the signal. Ethernet is a very fast communication network and it operates at a bandwidth of 10-100 million bits per second (bps) or at a 1 Gbits which is also known as Gigabit Ethernet [47].

In Ethernet network, when a node wants to transmit a signal, it first listens to the network. If the network is busy, the node waits. When the network becomes idle, the node (A node is any device that is connected to the network) transmits its signal. The reason for listening to the network is to prevent a case where two or more nodes transmit at the same time because this would cause a collision of the messages and result into the messages becoming corrupted. A corruption of messages can, however, occur especially in cases where e.g. two nodes listen to the idle network and decide to transmit a message at the same instant. In addition to listening to the network before transmitting, the nodes also listen to it while transmitting a signal to detect a message collision. In case a collision is detected, the node stops transmitting and waits a random length of time to retry again. If collisions occur too many times, the node no longer tries to transmit but instead sends a failure signal to the microprocessor trying to send the message. This media access method employed by the Ethernet is called the Carrier Sense Multiple Access with Collision Detection (CSMA/DC). [47]

The advantage of the Ethernet network is that it uses a simple operation algorithm and is very fast (10 MHz - 1GHz) especially in lower network loads. In addition to this, Ethernet cables are physically simple and relatively inexpensive. The disadvantage of Ethernet is the high possibility for message collisions at higher network loads.

In the HIL model, the communication between the HIL software and the real controllers occurs through analog and digital I/O and Ethernet communication. To be able to obtain effective communication between the HIL hardware and the controllers, understanding different computer network communication protocols (called fieldbus) is necessary. The communication protocols which are mostly used in the HIL model of this work are the IEC61850 standard based protocols and Modbus protocol. These protocols will be introduced in this section.

4.2.1 IEC 61850

Before the complex power substations of today, the substation automation systems employed simple and specialized protocol standards [48]. Since the devices were less intelligent, the number of transmitted data types were much smaller and the data types themselves much simple. However, a significant disadvantage was that different devices from different manufacturers used different communication protocols.

Therefore, the devices could not easily communicate with each other. This prompted a group of manufacturers and electric grid utilities from 22 different countries to design new international standards that define how to describe the devices in an electrical substation and how to exchange the information about these devices [49]. The collection of these international standards (14 individual standards) is called the IEC61850 standard. Currently, mappings in the standard are to Manufacturing Message Specification (MMS) protocol, Generic Object Oriented Substation Event (GOOSE) protocol and Sampled Measured Values (SMV) protocol [49]. These protocols are introduced in this section.

The IEC61850 architecture is illustrated in Fig. 25. The IEC61850 standard defines three communication paths: the path from a client to a server, the path from an intelligent electronic device (IED) to an IED (called the station bus) and the path from a measurement process to an IED (called the process bus). These communication paths employ the following protocols: MMS, GOOSE and SMV. The merging unit can be thought as a part of the SMV and it will be introduced below. The IEC61850 communication requires an Ethernet network and it can exist on the network simultaneously with other protocols e.gModbus. This architecture enables messages to be delivered to any device in the 2 to 4 ms time frame. [50]

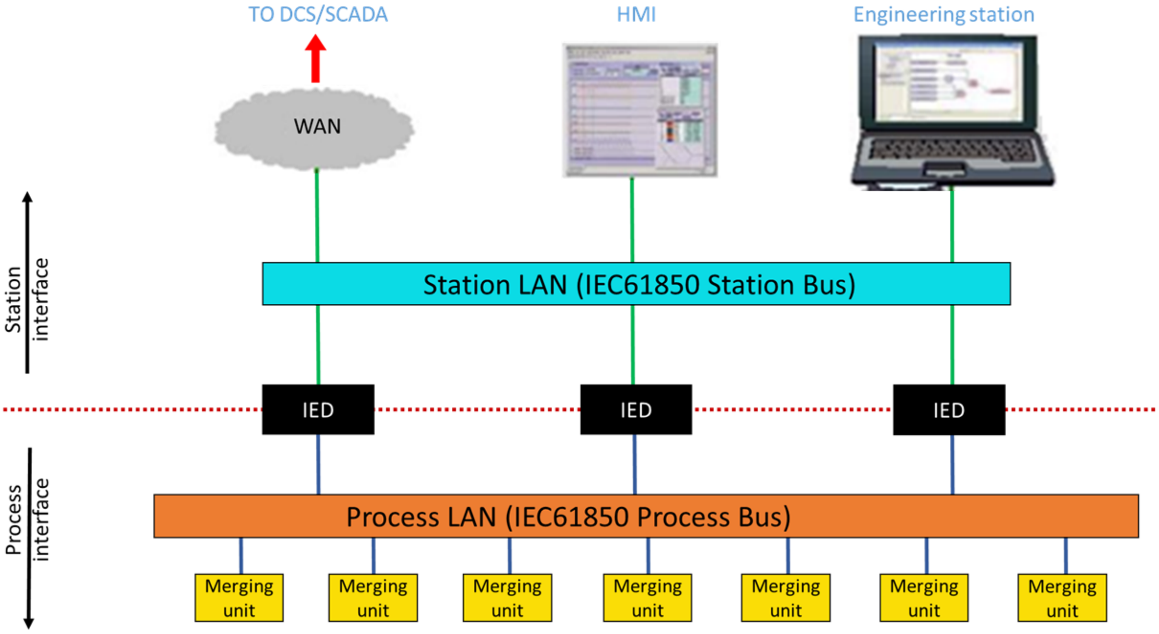

Figure 25: IEC61850 System Architecture [50]

Compared to the legacy protocols, IEC61850 standard is unique in a way that it specifies how the power system devices should organize data in a manner that should be consistent across all types of devices. This saves the user a lot of time and money because the devices can configure themselves without requiring much intervention from the user. E.g. if a current or a voltage is measured using sensors or measurement transformers and an input corresponding the measurement is put into an IED with IEC61850, the IED detects it and it can automatically assign it to a measurement unit. [51]

The IEC61850 provides numerous advantages that are not available using legacy protocols. Arguably the most important one is the reduction of costs for different applications. The IEC61850 enables the devices to exchange data over the station LAN which significantly reduces the need for different wiring and thus enables lower wiring costs. This also increases the safety of a system, e.g. an utility, because digitizing signals reduces the risk of electrical hazards. Also, devices with IEC61850 don't need much manual configuration because the client applications retrieve the needed information directly from the device or information can be imported in other ways. Often all that is needed is to set up network address to establish communications which enable lower commissioning costs. This also lowers device extension costs as there occurs no need to reconfigure devices when a new device is added. In addition to these, other substantial cost reductions occur in the equipment migration costs and integration costs. These cost reductions occur due to minimizing behavioral differences from one brand of device to another and due to the fact that the same networking technology is being widely used across the utility enterprise. [51]

Manufacturing Message Specification (MMS)

The MMS is an application layer protocol which is commonly used in industrial networks. Basically, the MMS is a messaging system that enables exchanging real-time data and monitoring and control information between devices in the industrial networks and computer applications. It was originally designed for remote controlling and monitoring of factory devices such as programmable controllers, robots etc.

The MMS architecture is based on a client/server model. The IEDs in the system have an MMS server which allows the device to be monitored and controlled by an MMS client. The client can usually be a control center, another IED or something similar. However, the real devices can be both clients and servers simultaneously. The server usually represents a set of objects which the client can access. These objects contain vendor specific features associated with the real device. The client sends the commands to the server and using these commands it can access the objects in the server. It can e.g. modify or delete the objects in the server. [52]

Unlike the other communication protocols, MMS is unique in a way that it does much more than simply provide a way for transmitting messages across a network. Actually, the MMS is not a communication protocol by itself as it also provides definition, structure, and meaning to the messages. This is usually what enhances the ability of the devices to communicate with each other regardless of brands or types of the devices. [52]

The benefits of using MMS communication are wide but the most important ones are mainly cost and efficiency related. E.g using MMS provides the user with a possibility to exchange control and process data information between different IEDs without the user having to create the communications environment himself. With other protocols this can often be too brand/type (or some other) specific or not specific enough to be possible. MMS, on the other hand, is defined by independent international standards bodies and is generic enough to overcome these problems. Another advantage of the MMS is that it provides a good data access which often is better than other communications schemes. [52]

Generic Object Oriented Substation Event (GOOSE)

The high-speed and multicast GOOSE protocol is an Ethernet based protocol that enables fast transmission of substation events, such as commands, alarms and indications, as messages. In GOOSE messaging, the real time sharing of information between devices in a substation is done through low-level Ethernet and it is becoming highly popular especially for time-critical events such as the protection of electrical equipment.

The IEC61850 standard connects all devices via a station bus. Since the communication occurs by the Ethernet network, it can run on the same connection simultaneously with other protocols. The protective signals (e.g. status signals) that are usually hard wired between the protective IEDs are also transferred to the bus as logical I/O which reduces the amount of required wires between the IEDs.

The Idea of the Goose messaging is illustrated in Fig. 26. Basically we can have a certain amount of IEDs connected into a common Ethernet bus. When one of the IEDs wants to send a message, e.g. it notices a sudden status change in the system and requires action from one of the other devices connected in the bus, it transmits a GOOSE message into the bus. Every IED connected to the bus receives the message. Depending on the functionality and the configuration of the receiver IEDs, only those that are configured to react to the message do so. The rest of the IEDs ignore it. The sender of the message will not receive back any kind of signal on whether the message has found its destination. Instead it will constantly keep sending the message until the reason that caused it to send the message in the first place is disappeared. That way, even if the first or second message gets corrupted, there is a higher probability of at least one of the messages to reach its destination. A typical GOOSE message is about 300 bytes long or 2400 bits. The speed of the GOOSE message can be very fast and its time on the wire can be as low as 24 μs. However, the receiving IED does cause some delay which can be typically around 1 ms. [50]

Producing the communication between IEDs using GOOSE messages has many significant advantages. As was mentioned above, it significantly reduces the hard wires between the devices. The communication between the IEDs occurs at high-speed via Ethernet and the setup and configuration of the devices is simple. In addition to the previous, using GOOSE messages offers the capability of sending analog and digital messages with a high speed which was not possible with other protocols. [50]

Sampled Measured Values (SMV)

The sampled values process bus uses merging unit (MU) technology to transmit and distribute sampled values data (usually voltage and current measurements) for

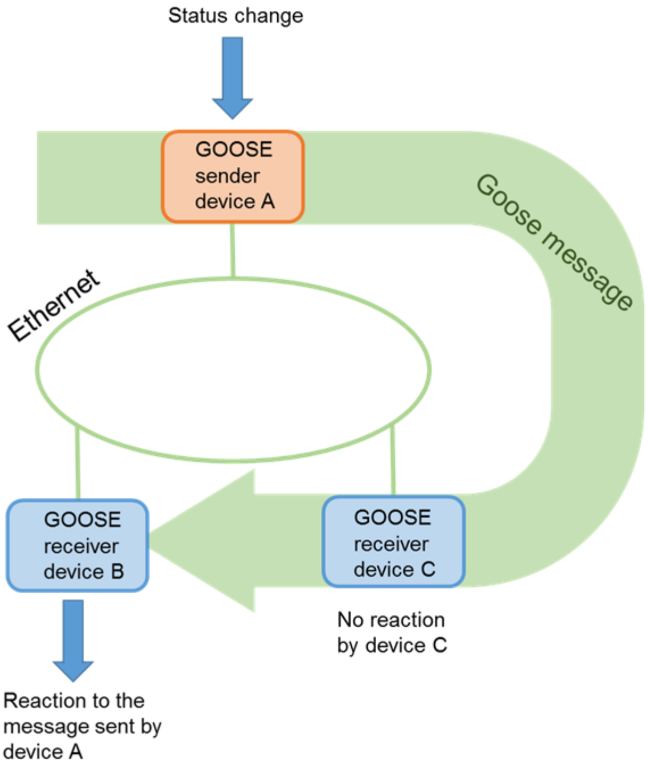

Figure 26: An illustration of GOOSE messaging. Device A notices a status change in the plant which requires some operation from device B. It sends a GOOSE message through the Ethernet bus. Both devices B and C receive the message but since the message does not affect device C, it simply ignores it. Device B reacts to the message and functions as is required.

control and protection applications. These sampled values are published in the substation network where any subscriber device can make use of them. Since the IEC61850 SMV protocol is based around the operation of the MUs, understanding the basic operation of the MU is necessary.

An MU is a unit that typically accepts analog and digital inputs and converts these signals to be able to transmit their data in a bus. E.g. in an electrical system where the current and voltage is measured using sensors, the analog outputs of the sensors are fed to the MU which samples these signals and generates sampled signals of them. Since this process causes some error in the time delay, it is very important for the MU to also compensate the error which it does by using the digitized sensor data.

The MU basically consists of three parts: a sensor part, a signal processor part and a communication part. The sensor part obtains and handles (e.g. amplifies and filters) the incoming analog signals and converts them to digital signals. The digital signals are then processed (i.e. time error compensation) by the signal processor part. Finally, the communication part then uses SMV protocol in Ethernet network to communicate with other devices such as IEDs. [53]

The benefits of using SMV protocol are shorter delivery times due to its simple nature and reduced wiring efforts which also reduces costs. Also, since a single MU device supporting SMV can deliver the measured signals to several devices, the number of required transducers is significantly reduced. The safety of the system is also increased by the elimination of current transformer and voltage transformer circuits. [51]

4.2.2 Modbus

Modbus protocol is an application protocol which defines organizing and interpreting data between two devices supporting Modbus communication. It was primarily developed, by a company called Modicon, for supervision and control in industrial automation systems and has since become a common method for transferring digital and analog I/O information and data between intelligent control and monitoring devices. Nowadays, Modbus is an open and public-domain protocol which does not require any royalty payment from the user to its owner.

Devices that use Modbus for communication use a master-slave technique where the master initiates transactions (which are called queries) from the slave. Basically in these queries the master either requests the slave to take a certain action or provide the master with a certain data. After the slave has taken the action requested in the query, it returns a response to the master indicating that the message was received. However, in case there occurs an error in the received query or the slave is simply unable to carry out the action in the query, the slave sends an exception message as a response which indicates an error. Usually, in Modbus communication any device can function as both master and slave and thus communication can happen in both directions. Masters can also either send messages to individual slaves or send broadcast messages to all slaves. However, if the master sends broadcast messages, the slaves will not respond to these queries. [54]

Nowadays a common way to use Modbus is on Ethernet network with a transmission control protocol and internet protocol (TCP/IP). The reason for combining Modbus with Ethernet is because Ethernet is widely accepted and it is supported by many manufacturers. When Modbus is used over Ethernet, it is usually called Modbus TCP. Basically TCP/IP is a two-layer messaging standard where the higher layer is the TCP and the lower layer is the IP. The higher layer, TCP, manages the packing of the messages into smaller packets that are sent over the Internet and then are transformed back into the original message by a TCP layer in the receiving end. The lower layer, Internet Protocol, handles the addressing of the packets to make sure the packet gets to the right destination. This way the TCP/IP makes sure that all packets of data sent are received in the other end and that the messages are correctly addressed and routed. [54]

Compared to many other communication protocols, Modbus protocol provides several advantages. It provides a reliable data transport mechanism between machines, is relatively easy to understand and is accessible to everyone thus providing the user with a very inexpensive method for communication between the devices. It is widely used by many manufacturers in industrial automation systems and often, different communication standards are even built on it. In addition to this, since Modbus TCP can be used on Ethernet network, it is fully compatible with the already installed large Ethernet infrastructure of cables, connectors, network interface cards, hubs, and switches. This makes adopting Modbus TCP communication in already installed devices relatively simple and easy. [54]

5 Simulation Model

In this section, we will propose a HIL model to be built for modeling and testing various control schemes in a DC power system on board a ship. The requirements that must be fulfilled by the model will be introduced and the proposed model (hardware and software) for the DC system will be discussed. The components of the model (real and simulated) will also be introduced in more detail. Finally, we will introduce some future objectives for the model and how the model could be expanded for wider uses.

In section 4.2, the importance of the IEC61850 standard to the HIL model was discussed. Both PMS and the EMS communicate with the HIL simulator using the GOOSE protocol on Ethernet network. Additionally, the relays, both virtual and real, use GOOSE protocol to communicate with each other and the rectifier controllers for the protection of the system. Therefore, Since most communication between devices (real or simulated) occurs through GOOSE protocol, the functionality of this protocol is crucial to the operation of the model. This work is based on an assumption that the GOOSE protocol can be provided by the HIL simulator. Therefore, before building the HIL model, it will be made sure by different tests that the HIL simulator supports GOOSE communication. However, these tests will not be discussed in this work.

5.1 Requirements for the Real-Time Simulator

To be able to maximize the usefulness of the eventual model and be certain that it can be expanded for future uses, it is important to set a certain amount of requirements that the real-time simulator must be able to fulfil. The following requirements are set for the simulator:

- **Real-time simulation.** The model must be able to produce real-time simulation for a large system and be able to function for a relatively long period (days). In addition to this, the simulator must be able to communicate with real controllers as fast as required by the controllers. Therefore, the simulator must have enough processor power and a short enough simulation sampling time. The HIL company will be responsible for delivering the HIL hardware which fulfils these requirements. The simulation time-interval must be in the range of 1-10 μs.

- **Automated Testing Environment.** The simulator must provide the controllers and relays an environment corresponding (as accurately as possible) to a real situation. The primary use of the eventual HIL model will be system level testing. Automated tests will be run around the clock and the simulator must be able to store the results which are of interest to the tester.

- **Hard wired I/O.** The real controllers and relays require some of the control, status and measurement signals to be received or transmitted as analog or digital signals, depending on the nature of the signal. In addition to this, the gate pulses for the generator rectifiers are produced as digital signals. Therefore, the simulator is required to be able to produce very fast (1-2 μs) digital and analog input and output signals.

- **Communication protocols.** Apart from the hard wired I/O signals, the rest of the communication between the real hardware and the simulated software occurs through fieldbus communication. The HIL simulator must support the IEC61850 protocols MMS, GOOSE and SMV. Especially GOOSE protocol, which is used e.g. for communication between the real relays and the virtual relays in the simulation model, is crucial for the functionality of the whole system. In addition to the IEC61850, the Modbus TCP protocol is also required to be supported by the HIL simulator. Initially, however, the Modbus TCP protocol will not be used in the HIL model but as it will certainly be needed when expanding the model in the future, it is already required as a precaution.
- **Communication hardware.** The communication is done through Ethernet network either on an Ethernet cable or optical fibre cable. Both must be supported by the HIL simulator.
- **Power amplifiers.** In some cases, the HIL simulator must be able to produce high voltages (up to 180V) and currents (up to 10A) for the real hardware controllers and relays. To produce these voltages and currents, the simulator must be able to correctly function with voltage and current amplifiers. The simulator should transmit digital signals to the amplifiers and the amplifiers should be able to produce voltages and currents corresponding to these signals.
- **Safety.** The safety level of the HIL model must be very high. The real power flow in the model is attempted to keep as low as possible but in the cases where power amplifiers are used, the high voltages and currents are required. However, these high voltages and currents must be well isolated from human contact and no danger situations should arise from them. Also, certain limits must be set to the power amplifiers so that no real hardware is damaged when testing the system in fault conditions.

5.2 The HIL System Configuration

The goal of this thesis work is to design a general HIL model for a DC power system on board a ship. This section will introduce the HIL system that will eventually be built primarily for development stage testing purposes. The real components in the model are initially only power electronic controllers and relays. They will be connected to the core part (HIL simulator), and together the core and the real components will form a simulation test loop. The software model components, which are mostly all large power requiring components, and the interfaces between the HIL hardware and the real hardware components will be discussed in this section.

The structure of the HIL loop is shown in Fig. 27. In this system, we have four generating units (which will be described in more detail in 5.2.1 and 5.2.2) with three real hardware controllers and one simulated controller. The reason for using only three real controllers is because three controllers is enough to run different tests, e.g. mutual interactions between the controllers, but also because using more hardware than is necessary raises the costs of the simulation. One controller is built as a virtual model which can then be copied in case a project requires more than three generating units.

The generators are connected to the main DC bus through virtual switches. These generator breakers are operated using real relays. The relays perform important monitoring and protection functions and therefore having them as real hardware is beneficial for testing fault situations. The bus-tie relays and all the rest of the components downside the DC bus are virtually simulated components. Eventually, the goal is to also use real controllers for the motor drives and the energy storage but for now, this work will only concentrate on the generating units.

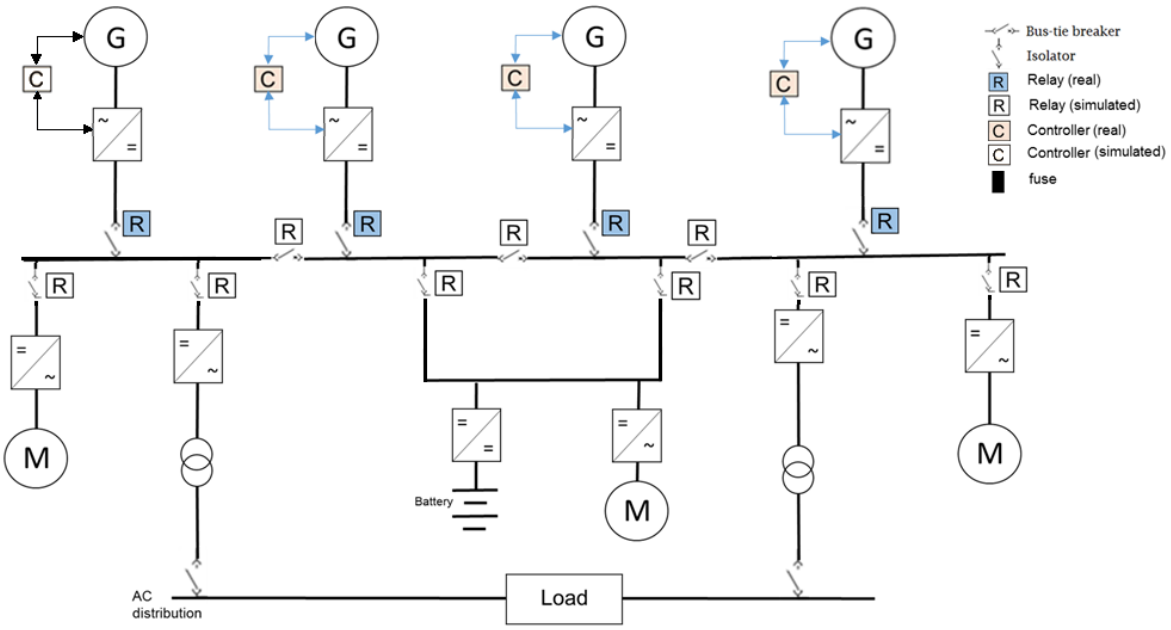

Figure 27: The proposed HIL model. The coloured relays and controllers are real hardware and the rest of the model is simulated using a HIL simulator.

The model proposed in Fig. 27 is a general configuration which attempts to include as many different configurations as possible. Therefore, it is not based on one particular already existing ship. The reason for using this particular model for the HIL system is that it contains different possible ways on how different components would be used in the simulation. E.g. the motor drives in the sides are directly connected to only one part of the grid. The grid in this configuration is divided into four sections which can be operated independently. If a fault occurs on that grid section where one of these drives is connected, that particular drive will be immediately disconnected from operation. On the other hand, the motor drive in the middle is connected to the grid in two sections and it also has an energy storage parallel to it. In case a fault occurs in one section of the grid, this drive can still be operated normally by disconnecting it from the faulty section and connecting it only to the healthy section. We call this a swinging motor drive.

5.2.1 Rectifier Controller Interface

The first interface between the real hardware components and the simulator hardware is between the power electronic controller and the power rectifier. In this HIL system, the power rectifier is a virtual model of a six-pulse thyristor rectifier bridge (see 2.2.3) and the power electronic controller can basically be any controller which can run the required software for gate pulses. The controller is used to control the generator rectifier as required by the DC power plant. The simulator provides the required voltage and current measurements for the controller. In return, the controller provides the gate pulses for the simulator.

The setup in Fig. 28 illustrates how the HIL simulation will be applied for the rectifier controller. In Fig. 28a, the setup is shown from the hardware point of view. The controller produces 24V digital firing pulses. In return, the simulator provides the simulation responses for the controller. These responses are analog signals, in the range of [-3.5, 3.5] V, provided through D/A interfaces. In Fig. 28b, the setup is shown from the simulation model point of view. In the simulation model, the converter input voltage (U_{conv}), input current (I_{conv}) and output voltage (U_{DC}) are measured and the analog signals corresponding to these values are provided for the controller. Notice, that the AC currents are also provided as voltages (on 1 Ω burden resistors) with low power.

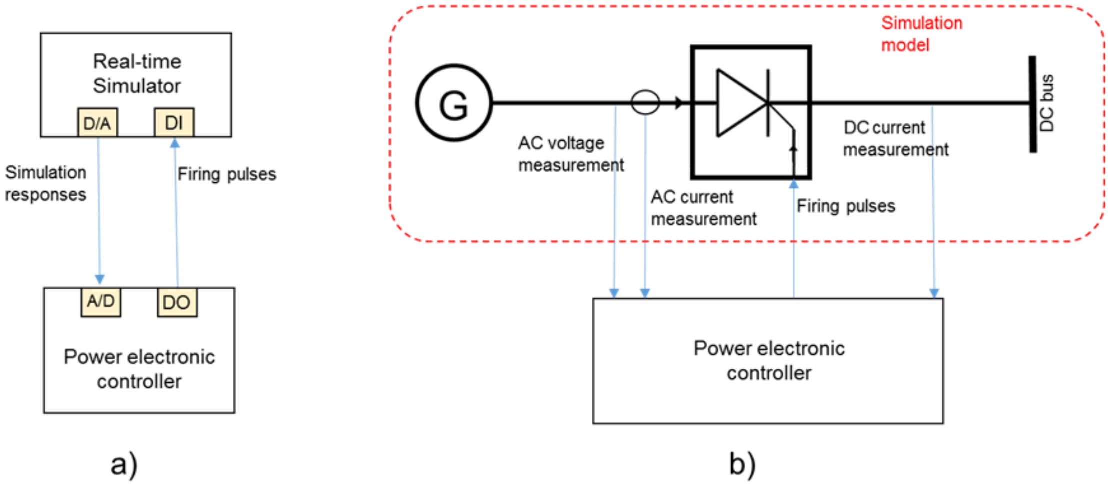

Figure 28: The system configuration of the rectifier-controller interface a) in hardware point of view and b) simulation point of view

In 4.1, it was mentioned that one of the most crucial aspects for correct operation of the HIL system, is the sampling interval of the HIL simulator. Regarding the analog outputs of the simulator, the sampling speed is not an issue as these do not require very high speeds. However, regarding the case of the firing pulses, the importance of the fast simulator sampling speed plays a bigger role. The thyristor bridge in the model is a line commutated rectifier and therefore, the switching of thyristors occur depending on the line frequency (and thus on the rotation speed of the generator shaft). In a DC power plant, the generators are run at variable speed (primarily at 50 Hz) and on occasions it can be up to 60 Hz. Since there exists six thyristors in the bridge and each thyristor is turned on and off in a cycle the maximum frequency at which switching (any thyristor) occurs would be around 720 Hz (6 x 2 x 60 Hz). Therefore, for the simulator to be able to react to the switching and make required calculations between them, the sampling frequency should be up to 100 kHz. Since the sampling frequency of the HIL simulator is at least as high as 0.1 - 1 MHz, this will not become an issue.

5.2.2 AVR Interface

The second interface between the real hardware components and the simulator hardware is between the real AVR hardware and the virtual generator model. The AVR can be a product by any company as long as it supports the interface introduced in this section. Notice that unlike the rectifier controller in the first interface, the AVR is not just a power electronic controller but instead it also contains all the AVR power electronics in it. Therefore, this interface differs a little from the rectifier controller interface. In this interface, the simulator needs to provide the required voltage and current measurements for the AVR controller and the supply voltage (from generator terminals) for the power electronic circuit of the AVR. In return, the AVR regulates the field current and provides it to the virtual generator exciter model.

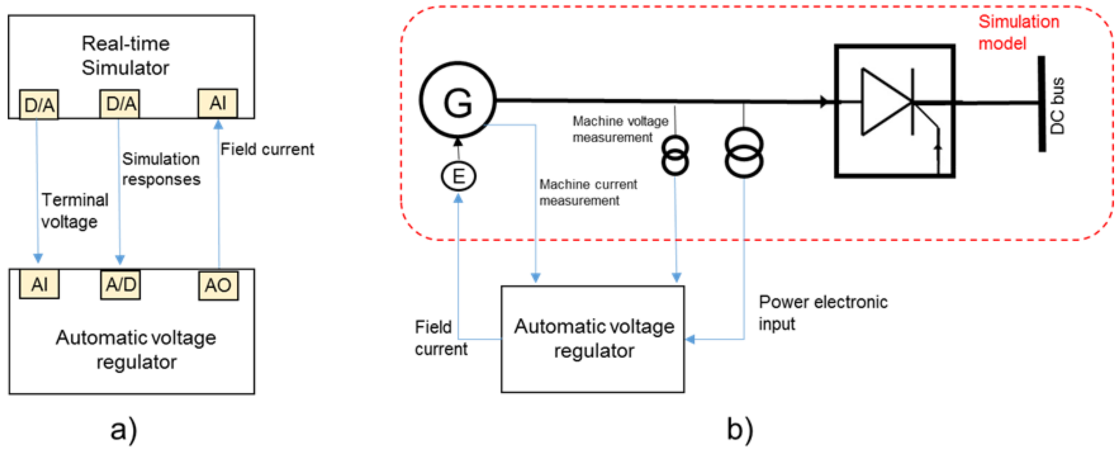

Figure 29: The system configuration of the AVR-generator interface a) in hardware point of view and b) simulation point of view.

The setup in Fig. 29 illustrates how the HIL simulation will be applied for the AVR. In Fig. 29a, the setup is shown from the hardware point of view. The field current produced by the AVR is a low power (<1 W) analog signal. The nominal value of the field current is 1-10 A depending on the size of the used AVR. The simulation responses and the terminal voltage are also low power analog signals corresponding to the values required by the AVR. In Fig. 29b, the same setup is shown but now from the simulation model point of view. In the virtual model, the terminal voltage is stepped down using a power transformer and a signal corresponding the transformer secondary voltage is provided for the AVR power electronics (low power analog signal up to 180V). The machine voltage is measured using a voltage transformer and a value corresponding this is provided to the AVR (low power analog signal, up to 180V). The machine current is measured using a 4000:1 current transformer. The nominal value of the current measurement is 1 A.

The reason for using a whole AVR instead of using only the AVR controller, like with the rectifier controller, is because many compact AVRs today are compact designs and accessing the controller connectors may become too difficult without damaging the device. To have a flexible system where we can use any AVR from any manufacturer, breaking devices to adjust them for the HIL hardware is not preferable. However, using the whole AVR, instead of using only an AVR controller, does also bring some difficulties. This is because in a normal situation, the power that is fed from the generator terminals to the AVR can be more than 1 kW. Discharging such a power into a discharge resistor (High power cannot be fed to the simulator) is economically unwise and it is thus avoided. Therefore, the power electronic converter of the AVR is supplied with a low power and in the output of the power electronic converter, a very small resistor is used. This way, even if the field current is up to 20 A, the output power of the AVR is only a couple of watts and it can easily be discharged as heat.

5.2.3 Relay Interface

The last interface between the real hardware components of the model is between the real Relays and the virtual generator isolator models. The relays used in this system can generally be any relay model from any provider. The general use and benefits of using relays were introduced in 2.3.2. In the DC power system, the main functions of the relays are controlling the generator switches and bus-tie breakers, monitoring the condition, current and voltage of the switches and forwarding this information to the rest of the control system. The communication between the relays and controllers occurs through IEC61850 GOOSE protocol.

The setup in Fig. 30 illustrates how the HIL simulation will be applied for the Relay. In Fig. 30a, the setup is shown from the hardware point of view. The relay controls the opening and closing of the generator switch with two 24 V digital outputs where a bit high means open/close. In return, the simulator similarly informs the status of the switch to the relay with a 24 V digital input (from relay point of view). In Fig. 30b, the same Relay setup is shown but now from the simulation model point of view. This figure illustrates how the real relay affects the simulation. The measurement responses are informed to the relay as analog signals. The current signal is a small 4..20 mA analog signal which corresponds to the current flowing through the switch. The voltage signal, on the other hand, is a $\pm 10\ V$ analog signal which corresponds to the voltage level.

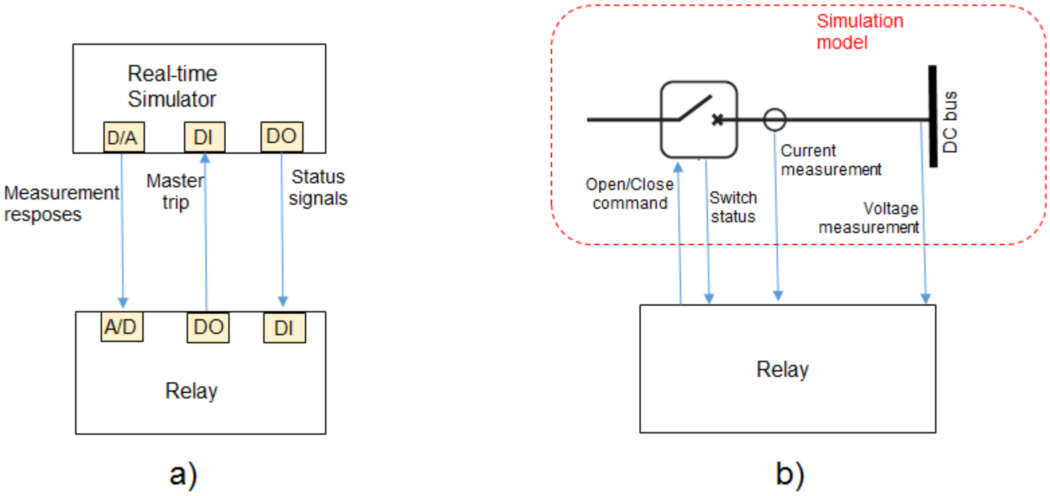

Figure 30: The system configuration of the relay-isolator interface a) in hardware point of view and b) simulation point of view.

Although relays are highly intelligent devices, much of their functionalities are limited in this HIL model due to using only a small number of I/O for the interface between the relay and the simulator. In this HIL model, the relays are mainly used only to open/close the generator switches and to measure the currents and voltages which are further informed to the rest of the control system by GOOSE messages. All of the protection relay functions, e.g. overcurrent protection and earth fault protection, are ignored here and therefore cannot be tested. The reason for this is because the primary objective of this HIL model is not to test the functionalities of single devices but instead to test the functionality of the whole system, e.g. the mutual interaction of the intelligent devices.

5.2.4 Software Model Components

The software components used in the HIL system are all the non-coloured components in Fig. 27. Initially, all these components will be ready made component models from the HIL schematic editor library. Since all of these models contain more or less simplifications of the practical situations, understanding the mechanical and electrical properties of these models is important when evaluating the results of the simulations. This section will provide the basic information of the mainly used virtual component models.

Synchronous Machine Model

The highest level HIL schematic figure of a three-phase synchronous machine (operates either in generator or motor mode) with a wound rotor is shown in Fig. 31. This model is used in the HIL system to describe the dynamic properties of the synchronous generator. The rotor in the model can be chosen as either salient or cylindrical rotor. The terminals A, B and C represent the stator winding terminals (three phases displaced by 120°) and the terminals R1 and R2 represent the field winding terminals.

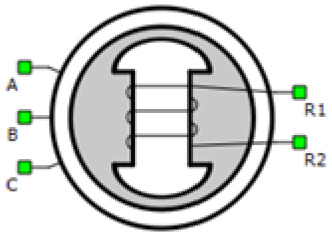

Figure 31: The highest level figure of a three-phase synchronous machine with wound rotor in the HIL schematic editor.

The synchronous generator block used in this system is represented by the seventh-order (also known as the standard model) state-space model where the dq frame is attached to the rotor. The electrical part of the model is based on the voltage and flux linkage equations introduced in 2.2.2. Therefore, operating the model requires inserting all the parameters of Equations (1) to (10) into the model. Similarly, the mechanical part of the model is based on the equations of motion introduced in 2.2.2 and the operation of the model requires also inserting all the parameters of Equations (16) and (17) into the model.

The standard model of the synchronous machine is often used when analyzing the dynamic and transient behaviour of the synchronous machine. It neglects the asymmetry of the stator windings, the higher harmonics in the air gap, the effects of external conditions, e.g. effect of temperature variation to the resistance values, the non-linearity of iron or the losses occurring in the iron core [55]. However, these effects are not essential for our testing and therefore believe the model is enough detailed for our purposes.

Thyristor Converter Model

The operation of a thyristor converter in rectifier mode was introduced in section 2.2.3. The thyristor rectifier model used in the HIL simulator is a simplified model of the real thyristor converter but enough detailed for requirements in this HIL model. The thyristors in this model are modeled as ideal switches with zero on-state resistance, infinite off-state resistance, and instantaneous switching transition. Therefore, when a thyristor is on, the resistance of the thyristor junctions are zero. On the other hand, when the thyristor is off, the resistances of the thyristor junctions are infinite.

This means there occurs no on-state nor off-state losses in the thyristor. Also, since the switching of the thyristors (ideal switches) occurs instantaneously, the switching losses are also zero. However, this model correctly represents the harmonics generated by the thyristor converter.

The highest level HIL schematic figure of a three-phase six pulse thyristor converter is shown in Fig. 32. Terminals A, B and C represent the terminals for the three-phase AC side terminals and terminals DC+ and DC- represent the terminals for the DC side. The converter operates either in the rectifier mode or in the inverter mode depending on the direction of the power flow. The gate pulses for the model are provided by real digital inputs by the real rectifier controllers (see 5.2.1). The user must specify which digital input of the simulator activates which thyristor after which that specific digital input pin will be routed to the chosen thyristor switch gate drive. When an input voltage is provided for the digital input, the respective thyristor turns on. This way the virtual thyristor converter is controlled by a real converter controller hardware outside the simulator.

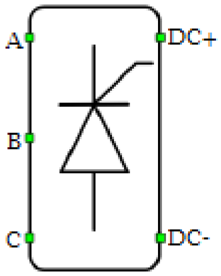

Figure 32: The highest level figure of a three-phase six pulse thyristor converter in the HIL schematic editor.

Transmission Line Model

Normally, in short distances, losses that are caused by the transmission lines can be ignored because of the relatively small size of the losses. In our model, the ships are small and the distances are relatively short. Therefore, we ignore the transmission lines used to e.g. transfer power from the generators to the main DC bus. However, to model the main DC bus and various DC links in the DC system, we use the ready made models in the HIL schematic library. Also, in case there eventually occurs a need to simulate larger DC systems, the need for modeling the cables may become significant. Therefore, having the cable models ready for use for future needs may become beneficial in the future.

HIL schematic editor contains a transmission line model (Fig. 33) which will be used in the HIL system. The user of this model can choose to configure the model to either neglect the shunt capacitances (Fig. 33a) or include them (Fig. 33b) in the model. In the model of Fig. 33a, the line is modeled as a simple inductive line with some losses in it. In smaller systems with low voltages, the shunt capacitors can often be ignored, due to their small value, and the transmission line model in Fig. 33a can be used. However, at higher voltages and longer line lengths, the effects of the shunt capacitors becomes significant and ignoring them leads to a less accurate model.

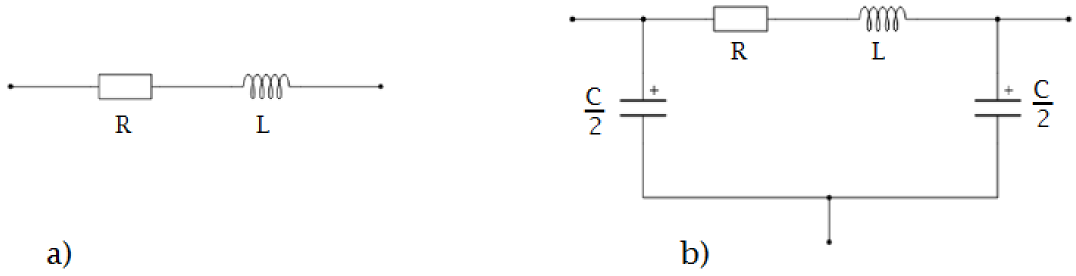

Figure 33: The equivalent circuit of the transmission line with a) neglected capacitances and b) included capacitances.

IGBT Inverter Model

The operation of a three-phase IGBT bridge converter in inverter mode was introduced in section 2.3.3. Similarly to the thyristor converter model, the IGBT converter model from the simulator schematic library is also a simplified model of the real IGBT converter but enough detailed for the requirements in this HIL model. The IGBTs in this model are also modeled as ideal switches with zero on-state resistance, infinite off-state resistance, and instantaneous switching transition. Therefore, like the thyristor converter, there occurs no on-state, off-state nor switching losses in the IGBT converter. However, this model also correctly represents the harmonics generated by the IGBT converter.

The highest level HIL schematic figure of a three-phase six pulse IGBT converter is shown in Fig. 34. Terminals A, B and C represent the terminals for the three-phase AC side terminals and terminals DC+ and DC- represent the terminals for the DC side. The converter operates either in the rectifier mode or in the inverter mode depending on the direction of the power flow. If the converter is controlled by a real controller from outside the simulator (which will eventually be the case in this HIL model too), the operating principle is similar to that of the thyristor converter. The user must specify which digital input of the simulator actives which IGBT switch after which that specific digital input pin will be routed to the chosen IGBT switch gate drive. An active high digital input activates the respective switch and an active low deactivates it. However, since initially the real inverter controller hardware are not used in this HIL model, the IGBT converters must be controlled from inside the simulator with a virtual controller model. The virtual controller used in the model will be a ready made model from the simulator schematic library.

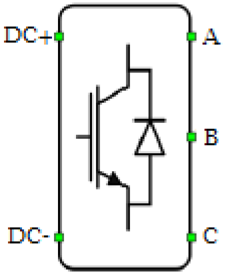

Figure 34: The highest level figure of a three-phase two-level IGBT converter in the HIL schematic editor.

Induction Machine Model

The highest level HIL schematic figure of a three-phase induction machine (operates either in generator or motor mode) with a squirrel cage rotor is shown in Fig. 35a. The machine in Fig. 35b also represents an induction machine but it is a doubly fed machine. These models are used in the HIL system to describe the dynamic properties of the induction motor used for propulsion. The terminals A, B and C represent the stator winding terminals (three phases displaced by 120°) which are fed with a three-phase voltage.

Figure 35: The highest level figure of a) a three-phase induction machine with a squirrel cage rotor and b) doubly fed induction machine in the HIL schematic editor.

The electrical part of the induction machine is represented by a standard state space representation, in stationary $\alpha\beta$ reference frame [56]. In $\alpha\beta$ model the stator and rotor voltage and flux linkage equations are divided into real and imaginary parts:

$$\underline{u} = u_\alpha + ju_\beta, \tag{44}$$

$$\underline{\psi} = \psi_\alpha + j\psi_\beta, \tag{45}$$

which are then used to describe the induction motor. The $\alpha\beta$ model is based on the voltage and flux linkage equations, (26) to (29), of the induction machine. Therefore, using this induction machine model requires the user to insert all the parameters presented in these equations.

Similarly, the mechanical part of the model is represented by the equation of motion and the equation of electrical torque, (32) and (33). Therefore, using this model requires inserting the parameter values of these two equations. The external load type can either be determined as either the torque or the angular speed of the shaft.

5.3 Expandability of the Model

One of the main requirements for this HIL model was the possibility to easily expand the system for different DC power plant configurations and for use of more real hardware in the model. The scope of this work was to design a HIL model for simulating an onboard power system in real-time. The goal of the HIL model is to provide an environment which can be used for executing various system level tests for complex power systems. Regarding the real hardware, this work concentrated only on the intelligent devices used in the generating units (AVR controller, rectifier controller and protection relays) and all the rest of the intelligent devices like inverter controllers or DC/DC converter controllers were ignored. Eventually, however, the goal is to expand the HIL model by building a more complete version of the onboard DC power system where functionalities like energy storage system operation or propulsion control can also be modeled and tested. Therefore, in this work it was also attempted to anticipate the forthcoming model expansions and design the model so that e.g. adding more real hardware would be relatively simple and easy.

While designing the HIL simulation setup for a DC power system on board a ship, many precautionary steps were taken to not limit the model for only a limited number of configurations. Regarding the virtual components, this was not a problem because adding and modifying them in the simulator software is possible at any time. Adding more real components on the setup, however, is more difficult due to two limiting factors. One is the limited CPU power and another is the limited number of available input and output ports in the simulator. Both of these can be added by buying more HIL simulator hardware from their provider. However, to do this, it is important to define in advance the type of the inputs and outputs needed for the future expansions.

To prepare for the future expansions of the HIL model, a possible interface between an inverter controller and the virtual inverter model is shown in Fig. 36. The inverter controller to be used in the model can basically be any controller type from any provider. In the setup shown in Fig. 36, the controller produces PWM pulses for the inverter in the software model and in return the software model produces measurement responses for the controller (see 3.4). As can be noticed, this setup is basically the same as the one introduced in 5.2.1 (albeit with some differences in the level of the measurement responses). The PWM pulses are produced as digital inputs and the measurement responses are produced as analog outputs which already exist

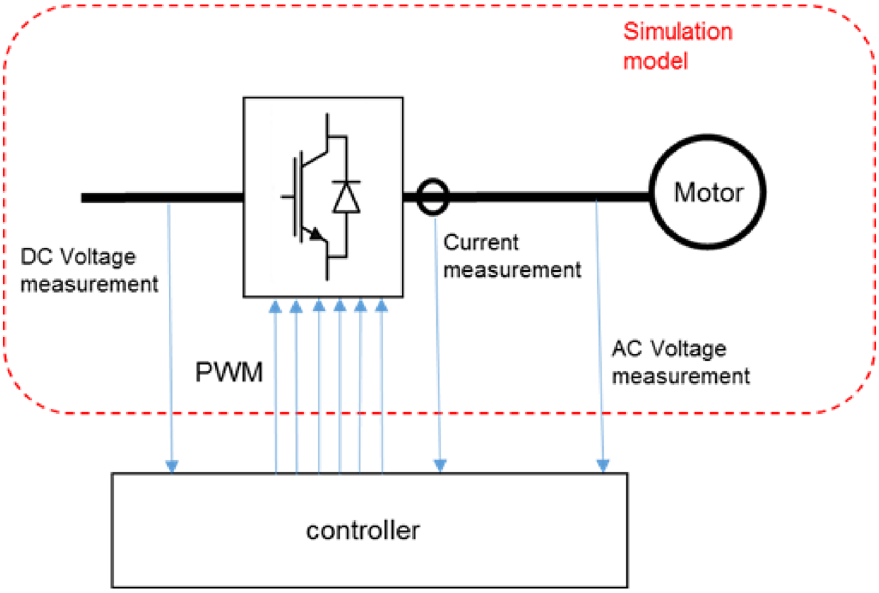

Figure 36: The system configuration of the inverter-controller interface in simulation point of view.

in the simulator hardware. Similarly to the inverter controller, it is also possible to connect a DC/DC converter controller to the simulator with basically the same kind of signals. Therefore, adding real inverter or DC/DC converter controllers to the model becomes simpler and achievable.

6 Summary

The objective of this work was to introduce the components and operation of a DC power system on board a ship and design a HIL simulation setup for modeling and testing a DC power system. Using DC as main energy carrier between generators and large consumers offers significant benefits compared to AC. One of the most important features that has helped shifting the interest from AC distribution towards DC distribution on ships has been the increased energy efficiency due to the possibility to use variable speed engines. The advantages of this are reduced fuel consumption and weight of the electrical system. Additionally, the DC power plant enables easier integration of an energy storage system which has the potential to further improve safety, efficiency and performance of ships with a DC power system.

To significantly reduce the cost of testing complete DC power systems and reduce the time to market of a large system, HIL simulation technique is seen as the most suitable solution. The HIL simulation is a real-time simulation technique which enables system level testing of large power plants without using any large power consuming components (generators, motors, grid...). In this simulation technique, large power consuming components are virtually modeled using a powerful HIL simulator. Intelligent devices (controllers, relays...) are then connected to it through hardwired signals and fieldbus communication. Together, the HIL simulator and the real intelligent devices form a simulation test loop.

The HIL simulator hardware was obtained from a third party company. Due to the limited amount of available hardwired inputs and outputs in the HIL simulator hardware, the number of real hardware to be tested was optimized to include only devices necessary to test the system operation regarding different control schemes. Especially the performance of functions required for blackout prevention and blackout recovery are of interest. For this reason, only some of the rectifier controllers, AVR controllers and protection relays were required as real hardware and the rest of the intelligence containing devices were virtually modeled using the ready built models the HIL simulator schematic library.

The future research will most likely investigate expanding the model to include several additional functionalities. One of the hottest prospects will definitely include the operation of a modern and efficient energy storage system. Additionally, propulsion motor control and possibilities to integrate different alternative power sources, e.g. fuel cells, will be of interest. The ground work for expanding the model for these different functionalities was laid in this work, and continuing from this work will be feasible.

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