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ESCOLA POLITÉCNICA

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**Hybrid Powertrains Analysis for Ship
Propulsion Using Energy Storage**

São Paulo
2018

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Dissertação de mestrado apresentada à Escola Politécnica para a obtenção do título de Mestre em Ciências.

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This work is dedicated to my family.

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*“It is the supreme art of the teacher to awaken joy in creative expression and
knowledge.”
(Albert Einstein)*

Resumo

As emissões dos navios já ocupariam a sexta posição entre os países com maior emissão no mundo. Isso pode ser explicado pelo fato de que as operações dos navios tem uma grande variação de demanda de potência, com isso a operação inteligente dos geradores a diesel é fundamental para a redução das emissões. A abordagem desenvolvida nesse trabalho integra o uso de sistemas de armazenamento avançados na operação dos geradores a diesel. A variação do ponto de operação dos geradores a diesel interfere diretamente no consumo e nas emissões, essa variação só é possível por meio do controle de frequência e tensão providos pelo sistema de armazenamento de energia. Nesse trabalho foram analisados o uso de baterias de lítio para diferentes pontos de operação do gerador a diesel. O principal resultado encontrado foi a redução das emissões e do consumo de combustível quando os geradores a diesel atuam por mais tempo em pontos de operação mais próximos de sua potência nominal. Os resultados encontrados nesse trabalho podem ser extrapolados qualitativamente para outros sistemas de potência offshore, como plataformas de petróleo e de perfuração, que operem com sistemas de baterias avançadas e geradores a diesel.

Palavras-chave: Sistemas Isolados de Potência, Emissão de CO_2 , Sistemas de Armazenamento Avançados, Controle de Frequência e Tensão.

Abstract

The ship emission would occupy the sixth position in the world biggest emitters ranking. It happens because the ship operations have a huge demand variation, to reduce the ship emissions is required an intelligent operation of the generators. This work aims at integrating advanced storage systems to the diesel generators operation. The variation of the operation point has a direct interference on the emissions and on the diesel consumption, this variation is allowed through the frequency and voltage control. The use of lithium batteries for various operation points of the generators is analysed. The mainly result obtained was the reduction on diesel consumption and on CO_2 emissions when the diesel generators operate for a long time closer to their nominal power. The results of this work can also be applied to isolated power systems equipped with advanced storage systems and diesel generators.

Keywords: Isolated Power Systems, CO_2 emission, Advanced Energy Storage Systems, Frequency and Voltage Control.

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List of acronyms

AVR Automatic Voltage Regulator

AP Adjustable Pitch

CPP Controllable Pitch Propeller

ECAs Emission Control Areas

ESRDC Electric Ship Research and Development Consortium

FPP Fixed Pitch Propeller

GHG Greenhouse Gases

HFAC High Frequency Alternate Current

IPCC International Panel on Climate Change

IPS Integrated Power Systems

INV Inverters

LNG Liquefied Natural Gas

MARPOL Maritime Pollution

MATLAB Matrix Laboratory

MVDC Medium Voltage Direct Current

MVAC Medium Voltage Alternate Current

PMS Power Management System

PSV Platform Supply Vessel

REC Rectification

VP Variable Pitch

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Introduction

This work aims at analysing the impact on the Greenhouse Gases (GHG) emission by the installation of advanced energy storage systems into the normal Integrated Power Systems (IPS) for a Platform Supply Vessel (PSV). A hybrid powertrain is a result of a battery connection to a IPS both power systems, IPS and hybrid, are described in this work. A battery connection enables the operation of the diesel engines at an optimal point, in an optimal point the diesel consumption is lower therefore the GHG emissions are also lower. We perform simulations over a standard routine to analyse voltage and frequency levels, moreover we perform analysis over the diesel consumption and the GHG emissions.

1.1 Ship Emission Regulation

This sections aims at clarifying the aspects of the recent regulations that were developed to stablish limits on GHG emissions, the three mainly gases (CO_2 , NO_x , SO_x) emitted are discussed. The Paris protocol established guidelines and targets that should be followed by the signatory countries to keep the temperatures limited at 2°C above pre-industrial temperatures. The demand of the CO_2 emission reduction began with the recent discussions over the climate crisis. The fifth assessment report of the International Panel on Climate Change (IPCC) reinforces that to reduce the risk of irreversible changes in the climate system, the global temperature must be limited at 2°C above pre-industrial temperatures. To reach this maximum temperature increase, a total of 176 countries have signed and ratified the Paris protocol, unfortunately the advances obtained with the Paris protocol are not applied to ships, which are responsible for 2.5% of global greenhouse gases (GHG) emissions. If the shipping emissions are left unregulated, these emissions can reach 17% of global CO_2 emissions, in 2050.

An recent study from the european parliament shows that to stay below the 2°C the shipping emissions should be -13% and -63% of the 2005 CO_2 emissions in 2030 and 2050, respectively. The global GHG emissions increased 25% from 1990 to 2010

whereas maritime transport increased 70% during the same period. On average this GHG emissions rose by 3% per year between 1990 to 2010, global GHG emissions, during the same period, only rose by 1.1%, as can be seen on [1].

The European regulation has been more restrict, in the recent years, with GHG and CO_2 emissions on Emission Control Areas from large ships navigating into EU ports. According to [2], the current global limit for sulphur content on fuel oil used in ships is 3.5% m/m (mass by mass), the new global limit is 0.5% m/m and it will be applied from 1 January 2020. This limit does not change the limit imposed to Emission Control Areas (ECAs) that is 0.1% m/m and is in force since January 2015. Fig.1 shows the NO_x limits for each Tier according to the Rated Engine Speed. Tier I standard entered into force in 2000, Tier II in 2011 and Tier III in 2016. According to [3], Tier I and II limits are global, whereas NO_x Emission Control Areas are covered by Tier III standard.

The main motivations to study ways to solve the ship emissions growth are the recent regulation created by the european parliament [4], the growth forecast on ship emissions by 2050 [5] and the increasing on media coverage on the topic [6, 7, 8, 9]. The increase of power density on lithium ion batteries opened markets for high power application [10], on the top of that the prices have fallen rapidly in recent years [11, 12].

The battery connection to the system, making it hybrid, will help the diesel generators to operate at their optimal points, it will save diesel and reduce the CO_2 emission. It is possible to operate at the optimal point in a hybrid system because the battery can work as a load when there is a power surplus and as a generator when there is a lack of load. This chapter aims to sintetize the rules and regulations that are in force in a document. In the recent years the ship's emission has been more studied and some organizations have discussed and created regulations that aims to reduce the GHG emissions.

One possibility to reduce the CO_2 emission can be achieved by using advanced energy storage system. Its use should not have negative impact on the vessel's power quality and reliability. The main objective of this work is to evaluate the impact on the frequency and the voltage levels of a platform supply vessel (PSV) during a mission. To deal with that, we have developed models to perform dynamic simulations using *SimPowerSystems/Matlab*.

1.1.1 Sulphur Oxides (SO_x)

According to [2], sulphur oxides or (SO_x) are formed in the engine, during combustion process, as a result of the existence of sulphur in the marine fuel. SO_x are present on the smoke emitted by the combustion of marine fuel, the sulphuric acid is formed by the oxidisation of the smoke in the presence of NO_2 , that works as a catalyst, the sulphuric acid is one of the major causes of the acid rain. Nowadays, according to the MARPOL Annex VI, the global limit for sulphur content in marine fuels is 3.50% m/m (mass by mass) it will be reduced to 0.50% m/m, effective from 1 January 2020 [13, 14]. This limit

does not change the limits of SO_x and particulate matter imposed to Emission Control Areas (ECAs) that is 0.1% m/m and is in force since January 2015. There are four existing ECAs: the North Sea, the US Caribbean ECA, the Baltic Sea and the Emission Control Area that includes most of US and Canadian coast, called as North American ECA. The mainly methods to reduce the emission of (SO_x) are: use of fuels with low sulphur, apply a scrubbing liquid to the exhaust gas reducing the SO_x to 95%, finally a good quality cylinder lubrication also achieves a SO_x emission reduction [15, 16].

1.1.2 Nitrogen Oxides (NO_x)

According to [17], Nitrogen represents 78% of the air mixture, whereas the oxygen represents 21%. At certain operation conditions, this air mixture, inside a marine engine, can form Nitrogen Oxides, (NO_x) are produced by the reaction between the nitrogen and the oxygen, because of the operating conditions is said that this reaction is dependent on peak temperatures and high pressure in the engine cylinders - above 1200°C the formation is significant and above 1500°C it becomes rapid. Whereas in [18] is shown the mainly causes to form NO_x in Marine Engines.

Some methods to reduce the emission of (NO_x) are following mentioned, mixing humid air to the combustion air before it goes to the cylinder can achieve a reduction by 70-80% of NO_x , as the technique mentioned before another technique mixes the combustion air to the gases exhausted by the engine, reducing the amount of oxygen presented on the combustion chamber therefore reducing the formation of NO_x , the next approach aims at using water to reduce the combustion temperature, since when the combustion happen at high temperatures the formation of NO_x [15].

In Table 1 is shown the Tier division established in the Maritime Pollution (MARPOL) Annex VI. As can be seen from Figure 1, which represents graphically Table 1, Tier III is the most stringent because it refers to the newest ships, built since 2016. The NO_x limits varies according to the engine rotational speed.

Table 1 – MARPOL Annex VI NOx emission limits

Tier	Date	NOx Limit (g/kWh)		
		n<130	130≤ n<2000	n≥2000
Tier I	2000	17	45 * n ^{-0.2}	50
Tier II	2011	14.4	44 * n ^{-0.23}	7.7
Tier III	2016	3.4	9 * n ^{-0.2}	50

Adapted from [18]

Figure 1 – NO_x limits according to Marpol Annex VI.

Source: Author

As described above there are different limits for each gas mentioned above, furthermore the composition of these gas varies according to the fuel, different than diesel, Liquified Natural Gas (LNG) does not contain SO_x on its composition. The next section adds more motivations of this project.

1.2 Motivation

The recent regulation created by the european parliament [4], the growth forecast on ship emissions by 2050 [5], the increasing media coverage on the topic [6, 7, 19, 20] are the mainly motivations to study ways to solve the challenge of ship emissions growth. The increase of power density on lithium ion batteries opened markets on which the batteries can operate at much higher power [10, 21], besides the fact that increasing on the power density, the prices of the lithium ion batteries have fallen in the recent years [11, 22].

1.3 Objective

The objective of this research is to analyze the impact of operating an advanced storage system in combination with diesel generators, as the demand of the ship has a huge variation, the battery can be used to keep the generators operating closer to their maximum nominal power. This additional ability would reduce the diesel consumption and reduce the CO_2 emission. Besides that, the impact of the use of the advanced storage system in the reliability is also investigated. The advanced storage system can have enough power and energy to substitute a generator for a few minutes in emergency

mode of operation, this mode of operation is called spinning reserve. From the electrical point of view our main objective is to analyse the voltage and frequency control provided by the battery for various operation modes.

1.4 Materials and methods

To achieve the objectives a PSV power system as in [23] was implemented on Matrix Laboratory (MATLAB) SimPowerSystems. The PSV power system were modelled for dynamic analysis using in time-domain approach. The determination of the operation point of the diesel generators were performed using the optimal dispatch of (! (!)HOMER). Additional models were developed in (!HOMER) to calculate the inicial dispatch values of power to supply the PSV demand. The simulations using the SimPowerSystems were set with these initial dispatch conditions and the control models to verify if the frequency and voltage were inside the limits. More details of the models will be discussed in chapter 3.

1.5 Publications

The published works during the Masters period are summarized below.

Publications in international conferences:

1. VIEIRA, G. T. T. ; PERALTA, C. O. ; SALLES, M.B.C. ; CARMO, B. ; Reduction of CO_2 Emissions in Ships With Advanced Energy Storage Systems. In: International Conference on. CLEAN ELECTRICAL POWER Renewable Energy Resources Impact (ICCEP 2017), 2017, Santa Margherita Ligure. proceedings, 2017.
2. VIEIRA, G. T. T. ; SALLES, M.B.C. ; MONARO, R. M. ; Voltage and Frequency Regulation in Marine Vessel's Electrical Power System. In: International Conference on. Environment and Electrical Engineering (EEEIC 2018), 2018, Palermo. proceedings, 2018.

1.6 Next Chapters

The next chapters of this master's dissertation are structured as follows: Chapter 2 presents a simplified overview on batteries, moreover this battery presents references of battery sizing and cost and show generic schematic of batteries.

Chapter 3 describes the ship power system topology, including: Generators, Distribution and Propulsion.

Chapter 4 report the analysis performed.

Chapter 5 presents the conclusions of this work and the future works that can be pursued.

Battery State of Art

This chapter aims at presenting a short overview on some battery technologies, contrasting them and highlighting its positive and negative points.

2.1 Battery Overview

According to [24], batteries can be divided in primary (non-rechargeable) and secondary (rechargeable). In the last years the batteries industry has undergone a tremendous growth, there was a increase on energy density and a decrease on battery cost.

The reduction on battery cost is the result of the popularization of batteries. Batteries has became popular because they can absorb the power peaks and valleys better than diesel generators that could be oversized, and therefore run out of their optimal point. Besides the advantage of covering peaks and valleys on some power systems, batteries can help to operate diesel generators on their optimal point consuming less diesel and emitting less CO_2 .

In a power system composed of batteries and diesel generators, batteries can improve the system reliability because they have a faster response than diesel generators , another point is that this system reliability improvement will not cost an environmental concern, since another way to improve reliability would be having two or more generators running the system, it would move the operation point of the generators to a worst point of operation.

In Figure 2 is shown a comparative between discharge time at rated power and system power ratings of different battery technologies and theirs basic characteristics [25].The comparisons presented in Figure 2 are very general and tried to show the reality in 2013, duration and power ranges are possibly broader because of the advance of the technologies. There are a few candidates that might fit in the needs of ships with special attention to the green area. The most common batteries are lead-acid and lithium-ion (or Li-Ion). However, flow batteries and NaS (sodium–sulfur) batteries could be an interesting option for systems that require high power rating and high periods of discharge[26].

Figure 2 – Power and discharging time characteristic of electrical energy storage technologies.

Source: Adapted from [25].

The requirements for ship applications are similar to microgrids or isolated power systems [27]. On [24] is set a list of minimum requirements in order to best achieve the battery selection. The next subsection shows different methods to calculate the size and the cost of batteries.

2.1.1 Battery Sizing and Cost

In [28] is shown how to calculate the levelized cost of the stored energy (LCOE), the LCOE is a relation between total installed cost for the total lifetime of the project and the energy injected by the battery. This work presents a calculation of the LCOE for three batteries technologies, a Lithium-ion, a Redox-Flow and a Lead-Acid.

In [29] the objective is to find an optimal operation considering the cycle-life degradation, two mechanisms are tested, variable C-Rate and variable efficiencies. This work shows that the more you operate at a high C-rate, the largest will be the decrease in the battery's State of Health (SoH). When the battery is operating under room temperature. In this work is also shown that the increase on the charging/discharging C-rates, leads to an quadratically increase of the power losses.

In [30] is presented a matrix that shows which technology is more suitable for each

application, moreover this paper shows that energy storage systems can have four mainly applications: Bulk Energy applications (energy arbitrage and peak shaving), Ancillary Service Applications (voltage support, frequency regulation, spinning reserve, black start and load following), Customer Energy Management Applications (power quality and power reliability), Renewable Energy Applications. It is also shown in [30] that the location of the storage system has a high importance because from this location usually derives its function. Although this work says that electrochemical batteries are not suitable for energy arbitrage there are some works that have studied this application [31, 32, 33, 34].

Based on the works cited above we can affirm that to size the battery we firstly should define which objective we are aiming at, the three mainly functions of energy storage systems in a power system, are:

- **Stability Control** - The increase on renewable energy brought a challenge of generation variability, moreover the use of diesel generators to support variations of the load can be not recommended regarding the regulations to reduce emission, besides the regulation batteries are faster and can attend the demand before the generators to allow the generators to ramp up slowly. The converter, that connects the battery to the grid, can also help on the voltage control doing the reactive power balance. In a grid without renewables, batteries can also increase the reliability, attending the critical loads if the generator fails. Sizing the battery to stability control should take into account which will be the role of the battery in the system, as said before operating a battery in high C-rates reduces the state of health, therefore diminishes the life cycle of the battery. Although the costs of the battery are a very important part of the investment in a hybrid grid, for some applications the cost of the batteries can be the minor problem compared to the result that a lack of reliability can cause;
- **Energy Arbitrage** - When a battery is sized aiming at this objective the battery should be sized aiming a profit, the profit can be obtained buying the energy when it has a lower price storing it and have a profit when the price increases, the amount of energy stored will represent the amount of profit, in this case the degradation of the battery and the net present value are extremely important, since a battery that degrades fast will not have a long life, therefore can not provide enough profit to pay its cost;
- **Emission Regulation** - As shown on Chapter 1.1, the emissions regulations have became very strict through the years for ships, the same can be said about the emission regulations for some islands and for some territories, California created, in 1967, the California Air Resources Board (CARB) and since then has reduced in 90% the black carbon emission. California is aiming at having 33% of electricity coming from renewable source, by 2020. CARB also aims at reduce the emissions

from agriculture and vehicles[35]. Size the battery to meet emission regulation usually will mean size a battery to force the generators to operate at their lowest emission/consumption point.

2.1.2 Generic Schematics of Battery

Generic models of batteries describe their electrochemical phenomena occurring using electrical active and passive components [36]. The generic models can be divided in:

(A) R_{int} Model

The R_{int} model, shown on Figure 3 is the most simplified model of batteries, in this model we do not consider a different value for the charge and for the discharge resistance. The open-circuit voltage, V_{OC} , is constant. This model can be considered for simulations on which the energy available is infinite and the transient phenomena can be neglected [36]. In our analysis we used this model since it did not require high computational effort.

Figure 3 – Battery electrical model R_{int} .

Source: Adapted from [36].

(B) Modified Thevenin Model

Figure 4 shows an modified Thevenin model, that can be also named as a modified version of the R_{int} model. This model has a resistance of charge and a resistance of discharge, it possibilities the battery to have a current to charge and another to discharge[37].

Figure 4 – Battery electrical model modified Thevenin .

Source: Adapted from [37].

(C) Thevenin Model

Figure 5 shows the Thevenin model, compared to the R_{int} this model is more complex, it considers the transient effects related to battery by adding a parallel RC dipole in series to the resistance[36].

Figure 5 – Battery electrical model Thevenin .

Source: Adapted from [36].

(D) RC Network Battery Model

Generally, the battery schematic can be represented as in Fig. 6. This model is an extended form of the Thevenin model where additional RC networks are connected in series to model additional internal voltage drops, the number of RC dipoles must be chosen according to the accuracy of the model [36].

Figure 6 – Battery electrical model RC network .

Source: Adapted from [36].

2.2 Li-ion Batteries

In [38] is presented a table containing several data from various batteries technologies, including lithium-ion batteries. Compared to these other batteries presented in [38], lithium-ion presents very good results when energy and power density are highlighted. The data presented on Table 2 shows diverse parameters for lithium-ion batteries.

Table 2 – Lithium-ion Characteristics

Adapted from [38]

Metric	Lithium-ion
Specific Energy [Wh/kg]	30-300
Energy Density [KWh/m3]	94-500
Specific Power [W/Kg]	8-2,000
Power Density [KW/m3]	56.80-800
Efficiency [%]	70-100
Lifespan [yr]	2-20
Cycle Life [cycles]	250-10,000
Self-Discharge Rate [%/day]	0.03-0.33
Scale [MW]	0.00-3.00
Energy Capital Cost [US\$/kWh]	200.00-4,000.00
Power Capital Cost [US\$/kW]	175.00-4,000.00
Application	Small/Medium Scale Energy Management
Technical Maturity	Mature Commercialized
Environmental Impact	High/Medium

Normally, battery installations have been sold in containers. The container should be big enough to store the batteries, the refrigeration equipment, the control systems and have enough space for maintenance. In a 20ft container, if we separate 60% of the space to

the batteries we would have around 19.82 m^3 available to install the battery system, using the values presented on Table 2, we can calculate that the power range of the batteries that can be installed in a 20ft container varies from 1.12 to 15.84 MW, whereas the energy range varies from 1.87 to 9.96 MWh.

The first rechargeable Lithium-ion batteries were put on Market by Sony, in 1991. These batteries have a liquid electrolyte, the lithium ions swing between the anode and the cathode [39]. According to [40], the first generation of lithium-ion batteries consisted of LiCoO_2 and graphite at the cathode and anode electrodes, after this battery others were developed, such as: LiNiO_2 , LiMn_2O_4 , $\text{LiNi}_{1-y-z}\text{Mn}_y\text{Co}_z\text{O}_2$, LiFePO_4 , $\text{Li}_4\text{Ti}_5\text{O}_{12}$, these batteries have reached the market at different levels and had intrinsic limitations derived from the redox mechanism related to the crystal structural aspects of the material[40].

During the tests of these many chemistries of Lithium-ion batteries, various types of electrolytes were tested, however liquid electrolytes are the most common electrolytes for these batteries, organic electrolyte solvents that are flammable should be avoided because the presence of these solvents can lead to a thermal runaway, increase the heat generation causing a fire [40]. There are many researches aiming the improvement of the Li-ion battery's performance, some examples are shown on [41, 42, 43, 44].

Lithium-ion batteries are the most mature battery for power systems applications, on [45] more than 700 projects using li-ion batteries can be found. Some of these projects will be highlighted here, in Australia a project which is under construction and is expected to be ready at August, 2019 aims to install 20 MW/34 MWh lithium-ion battery, alongside the batteries will be installed 56 wind turbines adding up 194 MW of generation capacity [46]. In California, more precisely in Orange County a 35 MW/140MWh lithium-ion battery is going to be installed by 2020 the objective of this installation is to give electrical capability and extra grid balance to that area [47].

2.3 Battery Choice

Although there is a vast number of batteries, some are still being developed and do not have a mature technology. Ships require batteries with a high power and energy density because of the space restriction, another point is that the batteries should have a higher charge and discharge rate since the batteries can help the ship power system in a failure of the generators so that the system does not collapse. As was calculated on the section before, a 20 ft container storing lithium ion batteries can contain up to a maximum power of 15.84 MW and up to a maximum energy of 9.96 MWh, using the average data presented on [38], 290 kWh/m^3 and 366.4 kW/m^3 , the average power installed on a 20 ft container is 7.25 MW and the average energy is 5.74 MWh. It means that this battery calculated by the average parameters can be operated for around 3 hours without recharge at the

rated power of the generators (4 x 1.85 MW) presented on the generic PSV studied in this work. Based on these requirements that are very specific for ship power systems we can find that lithium-ion batteries are the most suitable battery to be applied to the ship power system.

Hybrid Ship Power System Topology

Ship power systems are designed to fit in restrict spaces and to be reliable. A ship power system normally has two or three sections, each one with at least one generator and one thruster, these sections can be interconnected through breakers, these interconnections have to be fast enough to open before a fault reaches the entire system, the reliability lies on the selectivity study done. This study should take into account the number of generators and where they are going to be installed, the number of thrusters, the routine and the size of the ship.

Figure 7 – Platform Supply Vessel Power System.

The ship that is going to be studied is a PSV with four 1850kW diesel generators, one 910kW bow thruster, one 800kW retractable bow thruster and two 2MW azimuthal thrusters. To improve the optimal point and the reliability two 1MW/5MWh battery are going to be installed. The PSV power system is divided in two sections each one with two generators, one battery and two thrusters as shown on Figure 7 . The following sections are going to explain each part of the hybrid power system.

3.1 Diesel Engine Operation and Control

In the beginning, steam turbines were responsible to provide all the power demanded by the loads in ships [27]. Rudolf Diesel sells, in 1897, his first diesel engine. The advantage of his engine when compared to the others, that operate at that time, was that the cycle of operation of the diesel engine, was more efficient, when compared to the Otto Cycle, this advantage allowed a great increase of the diesel-engine industry. The Danish M/S Selandia, known as the most advanced ship powered by diesel engines at that time, was built in 1912 and was powered by two 935kW diesel engines.

In [27] is discussed about the ship power systems through the years. As is shown on [48] , the diesel engines are categorized as follows:

- Category 1: High-speed four-stroke engines with up to 100kW shaft power;
- Category 2: High-speed four-stroke engines with a shaft power between 100 and 10.000kW;
- Category 3: Medium-speed four-stroke engines with a shaft power between 5000 and 30.000kW;
- Category 4: Low-speed two-stroke crosshead engines with a shaft power between 100 and 10.000kW.

The diesel generator control is basically divided in Governor and AVR, they are responsible to control the frequency and the voltage, respectively.

3.1.1 Diesel Engine Control - Governor

Governors or speed regulators are an integral part of fuel injection systems in diesel engines [48]. Governors have the following functions [48]:

- Fuel-quantity control when the engine is started;
- Fuel-quantity control during engine idling;

- Maintain a constant speed (frequency regulation) at fluctuating loads, such as in gensets with alternating power decreases as well as in propulsion systems with varying cargo and weather conditions;
- Ensure that the maximum number of revolutions is not exceeded. Exceeding the maximum speed may cause damage.

It is established by notable classification organizations that the speed regulation requirements to operate engines as the main generator or as a emergency generator are in general [48]:

- Maximum Transient frequency variations can not trespass 10%;
- The system must return to the steady state frequency within 5s after the step load application or thrown off;
- The only case when the maximum transient frequency can trespass 10% is when the generator does not disconnect on over speed with 100% load rejection;
- The over speed protection will disconnect the diesel generator when the engine reaches 115%.

There are roughly three different types of governor [48]:

- Mechanical Governor;
- Hydraulic Governor;
- Electronic Governor.

3.1.1.1 Mechanical Governor

They are predominantly used in engines from the categories I and II. Mechanical Governor is a speed control device, this device has two suspended masses that goes up or down according to the change of speed with the help of inertia, as can be seen on Figure 8 [48].

Figure 8 – Mechanical Governor.

Source: Adapted from [49].

The mechanical governor is based on the principle of the centrifugal forces. It is connected through a drive to the engine, at first we suppose that the engine is running at a determined speed, an increase of the demand leads to a reduction of the engine speed, on this way the centrifugal speed is also reduced pulling up the sliding collar and then increasing the amount of fuel injected on the engine and increasing the speed of the engine. On the other hand, if the load is decreased the speed of the engine is increased and the centrifugal speed is also increased pushing the rotating weights of the governor away from the rotating shaft. When the rotational weights are pushed away they pull down the sliding collar restricting the amount of fuel and slowing the speed of the engine. The distance between the rotational weights and the rotating shaft is proportional to the speed of rotation [50] .

3.1.1.2 Hydraulic Governor

These governors are more sensitive than the mechanical ones, moreover, as shown on Figure 9 these governors have a hydraulic power piston, also known as servomotor that provides pump capacity to the governor, giving to the governor power to alterate the fuel control system [51].

Figure 9 – Hydraulic Governor.

Source:[51].

As shown on Figure 9, the hydraulic governor has a different working principle, on this governor the increase on fuel happens according to the variation of the oil pressure, moving the power piston upwards and downwards. The oil pressures the power piston after passing through the port, the pilot valve closes or opens the port according to the speed, when the measured speed reaches the reference speed the pilot valve closes and there is no oil passage, when there is a difference between the measured and the reference speed the pilot valve moves and the oil passes through the port.

3.1.1.3 Electronic Governor

These governors are often applied in diesel engines in categories III and IV and increasingly often in category II. Apart from controlling the set speed, electronic governors serve numerous purposes [48]:

- Excessively high speeds are avoided;
- Maximum fuel supply is limited;
- Maximum scavenging-air pressure is limited;
- When the engine is started, the electronic governor controls the maximum fuel quantity available ;

Figure 11 – Governor-Droop Control.

Source:Author.

The speed droop is a function of the governor that reduces the governor reference speed at an increasing load, in other words the variation on frequency makes the generator insert more or less power to the system. This governor allows the generators to operate at different points by setting different values for the droop. It is possible that the frequency of operation does not get close to the frequency of reference, it happens because the droop control is based on the speed error, the speed error is multiplied by a proportional gain resulting in the power dispatched from the generators to reduce the error, this proportional gain can cause a steady state error in frequency that remains while the governor causes a steady state change in the power required from the prime mover.

On 12 the subtraction of the velocity measured from the reference speed goes to the control system without the $Torque * Droop$ reduction, analysis performed with this governor do not allow a load sharing based on droop. On the other hand by using this governor, the generators operate following the reference frequency.

Figure 12 – Governor-Isochronous Control.

Source:Author.

3.1.2 Load Sharing Schemes

In [53] is presented four load sharing scheme:

3.1.2.1 Speed Droop

This mode of load division allows a partition of the load based on the value of the droop that is set [53].

3.1.2.2 Compensated Speed Droop

Power Management System (PMS) uses this method because it allows the adjustment of the frequency and of the participation of each generator. The PMS is necessary because it is responsible for moving the droop lines up and down on all the generators dividing the load in equal portions, each part is going to be attended by each generator, this is important because it allows a maintenance planning for all the generators this method also maintains a constant frequency through the load variations. The PMS needs to know, previously, if the generator is connected and which load is fed by this generator [53].

3.1.2.3 Isochronous

The isochronous mode of load sharing does an equal division of the loads between the generators. This mode aims at keeping the frequency steady regardless the variations of the system load. [53].

3.1.2.4 Master Slave

This control has two main parts [53]:

- Speed Droop : This loop sends a signal to the actuator to retain the main generator working at a defined point speed;
- Load Control: Applies an additional command signal, equivalent to the load, to the actuator.

The combination of the both parts keeps the generators frequency and allows the generators to cover the fluctuation of the loads. On our analysis we pursue simulations to analyse the governors set at isochronous and speed droop mode.

3.1.3 Diesel Engine Control - Automatic Voltage Regulator

Whereas the frequency control is obtained with the governors, the voltage control is obtained with the AVR. In a parallel operation between various diesel generators, the AVR is also responsible for sharing the reactive power between the generators[53]. AVR is considered a good option because it controls the voltage output through a field exciter of the synchronous generator for applications that require variable speed [54].

3.1.3.1 Matlab AVR

The AVR used on this matlab model is designed on Figure 13, as shown on Figure 13 the inputs from the machine are the reference value of the stator terminal voltage (V_{ref}), that is a constant set on 1.0, the measured value of the stator terminal voltage (V_t) is the square root of the sum of the squares of V_d and V_q , V_{stab} which is set to zero and the measured value of the stator field current (I_{fd}) that is the square root of the sum of the squares of I_d and I_q . The output that goes to the synchronous machine is the field voltage (E_{fd}). The constants were set according to [55].

The model shown in Figure 13 represents the model presented on the simpowersystems library of the matlab, to control the voltage of the synchronous machine, it is also known as an excitation system. This excitation system represents an alternate current alternator that drives a diode rectifier to deliver the field voltage required by the synchronous machine. The excitation system used is cited as the Type AC1A on the IEEE standard for excitation systems [55].

Figure 13 – Matlab AVR.

Source: Author.

3.2 Distribution System

Research efforts in power distribution are mainly related to improving dynamic performance and greater quality of service [56]. There are three main distribution system concepts in all electric power ship: Medium Voltage Alternate Current (MVAC), High Frequency Alternate Current (HFAC) and Medium Voltage Direct Current (MVDC) [57].

3.2.1 Generic MVDC Distribution Topology

Future naval warships that are equipped with synchronous generators to run the ship power system are one example to show that this topology has been considered to ships. Future naval warships are considered as a good system to receive the MVDC distribution

topology because of its high power demand. An example of a MVDC topology is shown at Figure 14.

This topology have been considered for electrical power systems that require a high power density and need a strong reliability, the Electric Ship Research and Development Consortium (ESRDC) has investigated the dynamic performance of the MVDC distribution to find if this topology can achieve this greater quality of service when a high power density is required [57].

The MVDC distribution is also the focus of many ship builders because this topology offers the possibility to rise the fuel-efficiency of the generators besides that this topology offers more flexible designs to the ship power system [58].

Figure 14 – MVDC Topology.

Source:[57].

3.2.2 Generic MVAC Distribution Topology

MVAC electrical distribution systems are very difunded throught many ships . Electric propulsion has advanced because of the advances in power electronics [58]. The frequency of distribution system must be fixed (kept constant) to maintain the 50 or 60 Hz (depends on the nominal value), independently of the loading conditions. This topology usually results in a sub-optimal use of prime movers (e.g. diesel generators) because of the variability of the load. This topology requires a coordination between the generators to keep them synchronized.

Figure 15 – Simplified Single Line diagram of a MVAC electrical distribution.

Source:[58].

Figure 15 represents a MVAC distribution topology which is powered by two pairs of generators (8.4 MVA +12.6 MVA), the system is redundant so through the connections X and Y the power feeder is changed. The Rectification (REC) and the Inverters (INV) are used to the variable speed operation [58].

3.2.3 Hybrid MVAC-MVDC Distribution Topology

Figure 16 shows a hybrid MVDC-MVAC topology, that is, as the MVAC topology, powered by the same generators. The difference here is that the propulsion variable speed drive is now powered by MVDC distribution system [58].

Figure 16 – Single-line diagram of proposed hybrid MVAC/MVDC electrical distribution system.

Source:[58].

3.3 Propulsion System

The propulsion system is the mechanism to thrust or to maneuver the ship, it should be designed respecting the individualities of each type of vessel.

3.3.1 Types of Propeller

Propellers can be divided into two main groups[48]:

- Fixed Pitch Propeller (FPP);
- Controllable Pitch Propeller (CPP):CPP are also known as Adjustable Pitch (AP) or Variable Pitch (VP) propellers.

3.3.1.1 Fixed Pitch Propeller

FP propellers are usually made of a very strong copper alloy. There is no variation of the angle of the blades, they are fixed and therefore the propeller pitch is fixed and cannot be modified. Because of the fixed pitch the propeller's performance depends on the marine conditions [48].

This type of propellers is applied to ships that does not require sophisticated maneuvering capabilities container ships and bulk carriers are some examples. These ships generally travel great distances on the high seas and do not berth frequently. They can safely enter ports to load and discharge aided by their bow thrusters (container ships) and/or by tugs (bulk carriers) [48].

3.3.1.2 Controllable Pitch Propeller

CP propellers differs from the FP propellers mainly because CP propellers have a hydraulic mechanism that allows the pitch control, therefore the angle of their blades is controllable, this propeller has a relatively large hub . Although the price is three or four times more expensive than the FP propeller, the large hub reduces the propeller efficiency [48]. The propeller is also more vulnerable in service than a fixed pitch propeller. CP propellers are often used in ships that require manoeuvrings. Ferries, container-feeder ships, dredgers, ro-ro ships, offshore vessels and others [48]. There is no need of change the direction of rotation of the engine when the CP propeller is used, in this case the ship can move forwards and in astern direction.

3.3.2 Transverse Thruster-Bow and Stern Thruster

Bow thrusters used in this work are impellers mounted inside a tunnel which is aligned athwart, this thruster system is also called transverse thruster. When the transverse thruster is located at the bow it is termed as bow thruster whereas when is located at the

stern, stern thruster [59]. The transverse thrusters can move the ships only in towards or backwards of the direction that it was installed, for this reason transverse thrusters are usually used for propulsion

3.3.3 Azimuthing Thrusters

Azimuthing thrusters are a subdivision of the Azimuthing and Podded propulsors, these thrusters differs from the transverse thrusters by the maneuverability, they can move to any direction and for this reason they are used in ships that require dynamic positioning, as the number of ships that require DP has increased on the recent years these thrusters have gained importance [59].

3.3.4 Direct Torque Control (DTC)

Control the torque of variable-speed drives brings some benefits described in [60]. DTC has been used to control Torque of induction machines and permanent magnet synchronous machines as can be seen on [60, 61, 62]. This control is named as DTC because the electromagnetic torque can be controlled by the stator flux-linkage space vector. A change on the stator voltage causes a change on the stator flux-linkage space vector [63].

Figure 17 – Schematic of the induction motor control by using DTC.

On Fig.17 is shown the DTC induction motor drive implemented on Matlab to control the Induction Motor, the DTC unit inputs are the current between lines A and B (I_{ab}), the voltage between lines A,B and C (V_{abc}), Flux and Torque. The DTC unit is the focus of Fig.17.

The inputs of the Electromagnetic torque and stator flux linkage estimator block are the components abc and ab of the voltage and current, respectively, these inputs are converted to dq to make possible to calculate the stator flux for both d and q components, the following equations show the calculation of flux and torque:

$$Flux_{stator_d} = \int (u_d - R_s * i_d) dt \quad (1)$$

$$Flux_{stator_q} = \int (u_q - R_s * i_q) dt \quad (2)$$

$$Flux_{stator} = Flux_d - j * Flux_q \quad (3)$$

$$Torque = \int \frac{3}{2} * P(Flux_d * i_q + Flux_q * i_d) dt \quad (4)$$

Where u_d, u_q are the stator voltages on the dq components, i_d, i_q are the stator currents on the dq components, R_s is the stator phase resistance of the induction motor and P is the number of pole pairs of the induction motor.

3.3.5 Matlab Propulsion Control

The matlab model for the propulsion control has two inputs that can be set by the user: the reference torque and the reference speed, these inputs are highlighted in blue on Figure 18. According to [59] the torque can be calculated by

$$T = K_T \rho n^2 D^4 \quad (5)$$

Where K_T means the thrust coefficient, ρ means the mass density of water, n means the propeller rotational speed (rev/s) and D means the propeller diameter (m). According to [59], the reference stator frequency can be calculated by:

$$f = \frac{n_p * N}{120} \quad (6)$$

Where n_p means the number of machine poles, f represents the stator frequency (Hz) and N is the reference speed (RPM). As can be seen on Figure 18 the propulsion control designed to this model is a three phase system, that is connected through a AC-DC-AC converter, highlighted in red on Figure 18, that isolates the system from frequency alterations in the propulsion.

The matlab block named as speed controller on Figure 18 is based on a PI regulator, the measured speed is regulated through the PI control to reach the reference speed, the outputs of this block are the set points of the flux and torque that are applied to the DTC block.

The DTC block receives other two inputs, the current and the voltage measured in the induction machine, from these last two mentioned inputs are calculated the estimated torque and the flux. The estimated flux and the set points of flux go to a two-level hysteresis comparator for flux control, whereas the estimated torque and set point of torque go to a three-level hysteresis comparator for torque.

The Braking Chopper is composed of an capacitor in parallel to a diode in series to a resistance, this block dissipates the energy produced by deceleration of the motor.

Figure 18 – Matlab Propulsion Control.

Source:Author.

3.3.6 Propulsion Model Validation

This subsection was designed to validate the DTC model presented on Matlab for the thrusters presented on our generic PSV. The two azimuth thrusters and the two bow thrusters of the PSV propulsion system were simulated using the system designed on Matlab mentioned before. On the simulations of the DTC, the torque was varied randomly.

Figure 19 – DTC's Rotor Speed results for 800kW and 910kW bow thruster and 2MW azimuth thruster.

Source:Author.

On Figure 19 is shown the curve of the rotor speed variation it takes around 5 seconds to reach the reference rotor speed of 1000 rad/s remaining steady from 5 to 60 seconds at 1000 rad/s.

Figure 20 – Results for 800kW and 910kW bow thrusters:(a)DTC's torque; (b)DTC's active power; (c)DTC's flux;(d)DTC's reactive power.

Source:Author.

On Figure 20 and Figure 21 are shown the results for the 800kW and 910kW bow thrusters and for the 2MW azimuth thruster, respectively. Figure 20(a) and Figure 21(a) are focused on the torque results, as can be seen the torque varies during the simulation aiming to reach the operational active power of each thruster. Figure 20(b) and Figure 21(b) show the active power results as can be seen at the end of the simulation the thrusters achieve the nominal power of them. The variations on torque causes an impact on flux and on active and reactive power. On Figure 20(c) and Figure 21(c) are shown the flux results for the 800kW and 910kW bow thrusters and for the 2MW azimuth thruster, respectively. As can be seen the flux is kept in a short variation range, the biggest variation for the three thrusters happened between 0 and 5 seconds, this variation happened because the rotor speed was increasing and reaching its operational point, 1000 rad/s. Figure 20(d) and Figure 21(d) show the reactive power results as can be seen the reactive power varies according to the variation on torque for all the thrusters, the thrusters operate with a power factor equals to 0.84.

Figure 21 – Results for 2MW azimuth thruster:(a)DTC's torque; (b)DTC's active power; (c)DTC's flux;(d)DTC's reactive power.

Source:Author.

The results shown above express that the variation on torque is highly related to the variation on active and reactive power. Although the results shown that the models are working and the 2MW azimuth thrusters and the two bow thrusters were designed in a matlab model, this model was not used on the analysis shown on the next chapter because of the computational effort required to run the model of the thrusters connected to the grid model. On the next chapter is shown how the load model was created to best represent the load demand required from the propellers and from the loads.

Power Generation Control

This chapter aims to explain the power quality regulation is displayed, presents a discussion about how the bus-tie should be operated, besides that the load curve development method is shown. Moreover are shown three analysis: the first aims at showing a diesel-electric system, without battery, operating during missions of the PSV, the second was designed to analyse the impact on voltage, frequency, diesel and emissions that the batteries could have on a hybrid PSV operating during the DP operation, the third analysis desires to present the gain of operating the diesel generators closer to their optimal point, leaving the frequency control to the battery.

4.1 Power Quality and Control Systems

This section discuss the requirements that ship power systems must attend to maintain in acceptable levels its power quality, it also discuss the importance of control systems to keep the system running under the limits of the standards.

4.1.1 Power Quality

As there is a high variability of the power demand in ships and sometimes the power step can reach some megawatts the quality of the electricity became very important as some equipments does not support a large range of variation in frequency or voltage. The ship power system has various operating conditions, such as: DP, manoeuvring, stand-by sea voyage, port and harbour operation. During these periods, the power demand changes significantly [64]. International standards were created aiming at stablish limits of variation in frequency and voltage [64]. Table 3 shows the PN-IEC-60092-101 that stablishes limits for ship power systems, named as “Electrical installations in ships–Part 101 : Definitions and general requirements”, it is based on the IEC [65].

Table 3 – Requirements of power quality stated by PN-IEC-60092-101 standard

Source:[65]

Parameter	Value
Steady voltage deviations	+6% -10%
Steady frequency deviations	$\pm 5\%$
Voltage Asymmetry	3%
Transient amplitude	5,5 UN
Increase/ decrease time of transient	1,2 μ s / 50 μ s
Total harmonic distortion (THD)	$\leq 5\%$
A single distortion (any harmonic)	$\leq 3\%$

Source:[65]

4.1.2 Control Systems

The control systems are very necessary to keep the different parameters discussed kept under the limits imposed in the norms, these control systems must coordinate the generation to attend the loads and coordinate the protection systems to contain an possible failure of pass to others equipments [66] . Ship owners usually report their problems related to power quality, some of these problems are listed in the following [66]:

- There is no communication between the control of the different systems, because of that control dynamic interations between these systems is difficult;
- The control of the reactive power is a problem;
- There is no monitoring of the power factor, since the reactive power control is a problem, an insertion of reactive loads or a filter loss can cause a voltage stability problem.

4.2 Operation Mode

The distribution system can be divided in two, three or four sections, these sections and be connected by use of bus-ties. Although there is a possibility to divide the distribution system in more than 3 sections it is not very common. Normally, the number of generators and thrusters are equally divided between two sections. The DP operations is the most dangerous operation in the PSV routine, for this reason is very important to have a good reliability. Dynamic Positioned (DP) vessels can operate on open or closed bus-tie mode. This decision is based on the operation and on the integrity of power operation. On one hand operating in closed bus-tie mode provides superior tolerance for dynamic positioning power plant faults but is not guaranteed that this operation mode will retain thrusters during certain types of power systems failures [67] . On the other hand, operating in open bus is required when retention of thrusters is necessary.

4.2.1 Closed Bus-Tie Mode

The International Maritime Organization published in 1994 “Guidelines for vessels with dynamic positioning systems”, this document treats about DP systems and establishes a division between them according to the characteristics that each group must have [68].

A growing awareness arising from closed bus-tie DP operations pushed some classification societies and industry organizations to move forward, developing rules and guidelines on which design requirements and test procedures are intended to elaborate the concept of “equivalent integrity of power operation”, while others maintained their position. This deviation between the societies represents a source of confusion, uncertainty and non-uniformity in the design requirements [?].

Some classification societies that the acceptance of High Voltage DP power systems operating in closed bus tie shall be based on the results of live short circuit tests (“fault ride through tests”). These tests consist in create a short circuit at the high voltage switchboard level, to prove that the power and the control systems are able to detect and isolate the fault, without any blackout occurrence [?].

Internationally recognized organizations that are in favor to perform these tests established a period of every 5 years during the lifespan of the vessel. On the other hand, classification societies that are not in favor of carrying out those type of tests, claim that they are dangerous to the personnel and stressful for the equipment [?].

The advances on switchboard protection relays have open the possibility to run the DP operation with closed bus ties, besides these advances another characteristic that helped to happen this operation in this configuration was the presence of thruster drives together with the new Power System Management that can prevent blackouts and can reduce the load in a more precise and faster way. Run the DP operation with the bus closed allows a more flexible utilisation of the generators increasing the fuel economy, it was not done before because the switchboard protections did not offer security. In [69] is shown that running the engines with an optimized loading offers a significant fuel saving .

4.2.2 Open Bus-Tie Mode

The operation with the bus-tie opened is required when the vessel is on the DP mode to ensure the availability of thrusters during any equipment fault but it reduces the overall power plant reliability, because an overload can happen if a generator fail and the control system does not work. During the DP mode, if one thruster fails and this fail pass other thrusters the vessel can move towards the platform or port and sink, to diminish this possibility the bus-tie is opened, so if a fault occurs in one of the thrusters the captain can stop the DP operation and move the ship away from the platform.

4.3 Power Routine Construction

The power routine was elaborated based on [70]. As shown on this work the percentage of time for each operation is equivalent to Figure 22, as can be seen the DP operation is the mission that last for more time, almost half of the whole routine, standby and loading in port are equivalent to 35% of the whole operation, and laden voyage and partial load voyage that are the two operations that require more power are equivalent to 17% of the complete routine.

Figure 22 – Percentage of time for each operation of the PSV routine.

The routine shown on Figure 23 was used in all simulations. The demand for each operation was based on the loads that the generic PSV analysed has, this is described on the following list:

- Port Operation** - During the Port Operation the ship is loaded, during this operation the thrusters are off, the load demand results from the variations on base load and the service load, around 1MW. Since this operation requires less power than the generators offer when operating at their optimal point, around 1.6 MW, in a hybrid PSV the batteries can be charged, utilizing the generation excess during this operation.
- Laden Voyage** - The Laden Voyage refers to the voyage between port and platform or vice versa, on which the PSV fully loaded, in this operation the power demand required from the thrusters varies closer to their maximum demand, the base load and the service load are also operating, therefore this operation requires around 6MW from the diesel generators and batteries in the hybrid PSV, since the demand is very high this operation does not look suitable for charge the batteries, on the contrary the batteries will probably help the generators to cover the loads.

- **Dynamically Positioning** - The DP operation is the most dangerous operation of the PSV in this operation the PSV stops by the platform. In this operation the thrusters are automatically controlled by the computers to keep the PSV steady. To increase the reliability the four generators are operating with the bus-tie opened, in case of a fault on one side the other side has enough power to close the operation and move the ship away from the platform. For safety reasons the battery is required to operate in spinning reserve during DP, it means that the battery must have enough energy to cover the DP demand for at least 10 minutes. The base load and the service load can be connected and the demand from the thrusters varies according to the wave and wind forces, the demand varies around 1.8MW
- **Partial Load Voyage** - This operation refers to a voyage between platform and port or vice versa on which the PSV is partially loaded, compared to the laden voyage the thrusters require less power, the base load and the service loads are connected and the demand varies around 5.5MW.
- **Stand-by** - The stand-by operation refers to the moment on which the PSV should stop offshore because the port or the platform are not ready to receive the PSV. The thrusters demand depend on the force of the waves, different from the DP operation this operation does not require that the ship must stay steady. A hybrid PSV can also charge the batteries during this operation or even use the batteries to power the system, disconnecting the diesel generators, the demand of the standby operation requires about 900kW.

Figure 23 – Power Routine.

The system shown on Figure 24 was implemented on Matlab to pursue the analysis, the system is divided in two sides, in both sides, the system contains two generators, one azimuth thruster, one bow thruster, one general load that can be a service load or a base

load and the energy storage system that is composed by the battery and the inverter, as can be seen between the two sides there are two bus-tie breakers, they are very important because as said before there is a considerable discussion about how the bus-tie should be operated if closed or opened, in our analysis we operated with the bus-tie opened when we performed an analysis on the DP operation and with the bus-tie closed for the other operations.

Figure 24 – Platform Supply Vessel Power System.

The next sections show the results for the analysis performed during the masters. Section 4.5 presents a comparison between opened and closed bus-tie mode, with the governors of the generators operating at droop and isochronous mode. Section 4.6 is focused on analyse the impact of operating the battery pursuing the peak shaving control, the diesel generator is set at the average of the load demand and the batteries cover the

fluctuations. Section 4.7 was designed to observe the gain of operating using the batteries to maintain the generators operating at their optimal point.

4.4 Diesel Consumption Curve

The analysis of diesel consumption and therefore emissions were performed based on the curve shown on Figure 25, as can be seen there is a considerable variation on operating the diesel engine with a low demand or at its optimal point, around 0.9 pu, the difference between these points can reach 15%.

Figure 25 – Diesel Consumption Curve

Since the emissions are calculated on this work as a constant in grams per liter of diesel operating at the optimal point of the diesel generator also leads to a higher reduction on emission.

4.5 Comparative between Droop and Isochronous Mode in contrast to Opened and Closed bus-tie

This section aims to compare two control modes of load sharing presented on subsection 3.1.2, moreover is traced a comparative between opened and closed bus-tie, presented on section 4.2.

Since this analysis is focused on the moment that the ship routine changes from the loading in port to the laden voyage, the load modelled on matlab was set to observe the worst case so the load representing the laden voyage demands 6.5MW from the diesel generators, it represents the maximum value shown on Figure 23 during the laden voyage mission, moreover the variation between the two missions is modelled as a ramp, it is done because as shown before the thrusters require a variance on the torque to achieve the nominal power, this variance is ramped.

As said before there is a discussion about how the bus-tie operated if it should be closed or opened during operation, if opened brings more security in case of failure and normally reduces the chances of exceeding the limits of frequency and voltage since the load is lower than when it is closed, if closed increases the possibility of running the diesel generators at its optimal point since the load is normally duplicated, therefore running the diesel generators with the bus closed reduces diesel consumption and GHG emissions.

4.5.1 Frequency and Voltage Control

This analysis is pursued in a diesel electric system, since it can be as a basis case to be compared to the hybrid system with the battery, therefore the frequency and voltage control is done by the governors and the AVR's.

Figure 26 – Active power , state of charge and frequency results for opened and closed bus-tie for droop and isochronous mode. The dashed line on frequency results means the limits of the PN-IEC-60092-101 for frequency.

As can be seen when we compare the frequency results for open and closed bus-tie on Figure 26, the case with the governors operating sharing the loads by a droop and with the bus-tie closed presents the frequency value most far from 50 Hz, that is the frequency reference.

Figure 27 – Reactive power and voltage results for opened and closed bus-tie for droop and isochronous mode. The dashed line on frequency results means the limits of the PN-IEC-60092-101 for frequency.

There is also a difference between the frequency reference and the final frequency presented by the case with the bus-tie opened and the load sharing being also done by a droop. This difference between the reference frequency and the final frequency for both approaches of bus-tie mode, is higher according to the number of diesel generators. Even though the final frequency for both cases on which the droop control was applied is not 50 Hz, its value is still allowed according to the norms. It can also be seen that more generators produces a impact on final frequency when droop control is used.

When the isochronous control is used the frequency at 80 seconds is 50 Hz, it shows

that the isochronous control brings a best response when the variability of frequency must be considered, here we also can compare the system operating with the bus-tie opened and closed, when it is opened the maximum frequency variation represents 0.28% whereas when it is closed this variation reaches 0.66%, representing more than the twice of that is presented when the bus is opened. It can also be seen that the generator set installed on this PSV system can support the highest load variation that can occur. The variations on frequency can be reduced by using batteries since the batteries have a faster response to cover the load demand.

Whereas on Figure 26 can be seen that batteries can help on controlling frequency since there is a small variation when only generators are operated, it cannot be said when the voltage results are analysed on Figure 27, the voltage results on the system without battery presents good results keeping the voltage very close to reference voltage of 1 pu. Batteries on voltage control can help as a backup in case of failure of the AVR's.

4.5.2 Diesel Consumption and Emission Analysis

To conclude the analysis over the discussion about the load sharing and the bus-tie operation, table 4 was created, it shows a value of reduction compared to the best case, isochronous closed bus-tie, that was achieved in this 80 seconds of simulation. The diesel consumption was based on the curve shown on Figure 25. As can be seen, the operation with the bus-tie closed produces the best results, for droop or for isochronous control, comparing isochronous to droop the first one presents a slight gain when compared to the other in both cases of the bus-tie operation mode. The discussion about the bus-tie operation mode must be pursued with careful since the reduction on diesel consumption and on GHG emission must be contrasted to the reliability and safety gain obtained by operating with the bus-tie opened.

Table 4 – Diesel Consumption and GHG emissions - Negative values represent an increase of consumption.

Case	Reduction on Diesel Consumed (%)	CO_2 reduction (%)	NO_x reduction (%)
Isochronous - Closed Bus-tie	—	—	—
Droop - Closed Bus-tie	-0.71%	-0.71%	-0.71%
Isochronous - Opened Bus-tie	-16.15%	-16.15%	-16.15%
Droop - Opened Bus-tie	-16.49%	-16.49%	-16.49%

Besides presenting the best results for diesel consumption and GHG emission, operating with the bus-tie closed in the isochronous load sharing mode also presents the best results for frequency and voltage, by that we can choose the isochronous mode as the best control mode for governors considering our analysis, moreover even considering that operating with the bus-tie closed can presents a higher frequency variation when compared to

the operation with the bus-tie opened, it achieves the highest reduction when compared to the other cases analysed, since the frequency variation is very far of extrapolating the frequency limits it can be chosen as the best mode of operation. Finally, based on the frequency and voltage levels analysis and on the diesel consumption and on the GHG presented emission we can say that our analysis presented that the best mode of operation is with the bus-tie closed and with the governor operating at the isochronous mode.

4.6 Peak Shaving

To perform the analysis of Peak Shaving we defined that the generators and the batteries would contribute to keep the frequency and the voltage under the limits set in the norm cited before. To set the generators to the average value of the loads two techniques were applied as shown on Figure 28 :

Figure 28 – Platform Supply Vessel Power System.

The two techniques are described in the following:

- **Variable Mean** - This approach requires a previous knowledge of the load, in our case we created two load signals one is delayed from the other, the delayed signal goes to the variable mean block and the signal not delayed is the load source, the

delayed signal goes to an accumulator that sums the values of the input and after five seconds is cleared, the value accumulated at the fifth second is divided by five and delayed in one,two,three and four seconds, then these delayed signals are summed to the signal originated from the division per five of the accumulator, the output of the adder is the power reference.

- **Washout Filter** - The washout filter is used to soften the variations of the load, it rejects steady state inputs, while passing transient inputs. The general transfer function of a typical washout filter takes the form:

$$H(s) = \frac{s}{s + a} \quad (7)$$

The battery is connected to the system through an mosfet inverter, the battery role is to cover the variations of the load, whereas the generators are kept on the average of the loads. To control the dispatch of the battery, we developed the battery inverter control shown on Figure 29, it controls the injection of active power to control frequency and reactive power to control voltage by using as inputs the power reference signal which is the output of the techniques mentioned before.

Figure 29 – Battery Inverter Control Scheme for Peak Shaving.

The battery control scheme is shown on Figure 29, the first step is to change the abc axes to the $dq0$ axes, with the voltage from the abc axes we can measure the frequency and the angle of the positive-sequence of phase A. This angle will be used to obtain the Voltage and the current in the $dq0$ axes. The voltage and currents obtained by the transformation from the abc axes to the $dq0$ axes are inputs to the control scheme as shown on Figure 29. The reference current of the axis d is obtained dividing the $ActivePower_{ref}$ per $1.5 * V_d$, V_d is the voltage calculated of the d axis.

The reference current is subtracted from the measured current in each axis, this value pass through a PI control which will reduce and integer the difference between the currents. To calculate m_d we sum the result of the PI control with the $V_{d_{measured}}$ and

subtract from this sum the multiplication of the $Iq_{measured}$ per $\omega * L_{grid} \cdot L_{grid}$ comes from the RL filter used for protection and as a filter, the design of the RL filter is explained on [71]. To calculate m_q we sum the result of the PI control with the $Vd_{measured}$ and with the multiplication of the $Id_{measured}$ per $\omega * L_{grid}$. To finish m_d and m_q pass through a mux and the result is multiplied per 2 and divided per V_{DC} , the result is the V_{ref_dq} to change back to the abc axes we mux the V_{ref_dq} to zero and the result on the abc axes goes to a PWM generator, that generates a signal to control the inverter.

In this analysis, the load was modelled as if the PSV came from a standby moment, with no considerable power requisition from the thrusters, and then started the DP operation, here since the power requisition from thrusters is lower than on laden voyage, that was presented on the last analysis, the ramp to achieve the DP demand is almost a step since the thrusters achieve their requisition faster. The DP demand modelled has a variation because our focus here is to analyse the battery covering the peaks, keeping the generators steady at the average load, the average load is similar in power to the DP operation. The voltage and frequency levels, the diesel consumption and some GHG emission are analysed. The first results are for the system without battery and after are shown the results for the system considering the two techniques explained before.

4.6.1 Results without battery for Peak Shaving

This first results does not includes the battery in this simulation the system considered has the thrusters, the generators and the general loads. The load required from the thrusters varies because in a real operation they are controlled by the DP control, that measures the wind and wave forces to find the necessary force that each thruster should receive to keep the PSV steady.

The generators will change their operation point to support the variation of the load caused by the step. As can be seen on Figure 30, the step is applied at 10 seconds, approximately, it causes a variation on the frequency, even though the drop on the frequency level is deep it does not reach the limit of 47.5 Hz, a smaller variation on the reactive power causes a variation on the voltage level, that almost reaches the limit of 0.9 pu. After the step application, starts a moment that is similar in power to the DP operation in this moment the load variations cause a perceptible variation on the voltage and on the frequency levels.

Figure 30 – Results obtained by the application of a load step to the system without batteries.

The next section show the battery connection, that was tested to reduce the variations on the frequency and voltage levels.

4.6.2 Results with battery for Peak Shaving

This analysis consider both techniques, shown before, in comparison to each other and to the case without battery.

As can be seen on Figure 31 the variable mean does not increase the time necessary to the generators reach the 2 MW power, whereas the washout filter increase, it takes approximately 10 seconds to them reach 2 MW of active power in the washout filter approach. Since the loads are connected at the same moment for all cases this period that the generators take to reach the power demand are supported by the batteries it causes a reduction on the State of Charge(SOC) that shows, in percentage, the amount of energy that the battery still has. As can be seen the case, on which was applied the washout filter approach has a significant reduction on the SOC level when the step was

applied whereas in the variable mean case the reduction is small and occurs after a positive variation before the application of the power step.

Figure 31 – Active power , state of charge and frequency results of a load step response for cases with and without battery.

Analysing the frequency levels we can see that the increase of the time caused to the washout filter helps the frequency levels, since the variation for this approach is minimal. The use of batteries also helped on the variable mean case, it causes a small reduction on the frequency level that can be explained when we look to the active power dispatched by the batteries, the batteries help when the load is connected it can be confirmed by the small variation of the SOC level.

The battery connection also helps during the period called as DP operation, on which active and reactive power reaches their maximum values, that occurs between 30 and 60 seconds, during this period the variations on frequency are smaller when the washout filter is applied compared to the variable mean case and to the without filter case.

Figure 32 shows the variation on the reactive power and on the voltage level. As said

before the inverter control was designed to control active and reactive power, controlling both powers the inverter helps on the voltage and frequency levels. Looking to the upper voltage level we can say that both approaches present good results, for the case without battery the maximum voltage level reaches 1.04 pu. Looking to the voltage drop on Figure 32 even though the voltage drop is reduced when the Variable mean approach, the washout filter also presents the best results when the voltage levels are analysed, the variation on voltage is significantly smaller when we compare to the variable mean or to the without battery case.

Figure 32 – Reactive power , state of charge and voltage results of a load step response for cases with and without battery.

From the analysis of both techniques with the case without batteries we can see that the batteries help the system to keep the voltage and frequency closer to their reference points, 1 pu and 50 Hz, respectively. Contrasting both techniques we find that the washout filter presents the best results.

4.6.3 Results for Diesel Consumption

The consumption curve of both diesel engines is shown on Figure 25. As can be seen from Figure 25 the point on which the engines operate have a higher importance on the consumption and emission, that is strongly connected to consumption.

The following calculations are done by focusing on the DP operation, from 30s to 60s of the simulation performed. In order to calculate the amount of diesel consumed, we first determine that the diesel used was the Marine Fuel Oil, that has a volumetric density is 0.97 kg/liter, then we plotted a curve comparing energy x consumption (liters/hour) and integrated the value for the simulation between 12 and 60 seconds.

Figure 33 – Consumption for both approaches compared to the without battery case.

To calculate the amount of diesel spent to charge the batteries we took the energy at the end of the simulation and subtracted from the energy at the beginning for both approaches, then we convert this difference of energy by calculating the amount of diesel that the diesel generator would spend to produce this energy operating at its best operation point, and we sum this diesel amount to the total diesel amount spent during the last 30 seconds of simulation.

Table 5 – Diesel Consumption - Negative values represent an increase of consumption on DP operation (from 30 to 60 seconds of Figure 31).

Case	Reduction on Diesel Consumed (%)	Reduction on Total Diesel Consumed battery charge + operation (%)
Without Battery	—	—
Variable Mean	-0.12%	-11.2%
Washout Filter	-0.12%	-15.54%

Table 6 – CO_2 and NO_x Emissions - Negative values represent an increase of emission on DP operation (from 30 to 60 seconds of Figure 31).

Case	CO_2 reduction (%)	NO_x reduction (%)
Without Battery	—	—
Variable Mean	-0.115%	-0.115%
Washout Filter	-0.115%	-0.115%

Comparing Fig.33 to Table 5 we can see that the approaches taken does not reduce the consumption because their operation range is worst than the operation without battery, on the other hand if we analyze Fig.31 we can see that there are 12 rises with different angle variations during the last 30 seconds of operation to the without battery case whereas for the variable mean there are only two rises that do not have a high variation of energy, for the washout filter case we cannot count any rises because the mean is calculated every second so the variations are not instantaneous.

4.7 Frequency Control via Battery

In this analysis we aimed to keep the generators operating closer to their optimal point(0.8-0.9 pu), forcing the generators to operate in a pre-determined point of active power require a exclusion of the governors, that control the frequency, from the system. The surplus generation is used to charge the batteries, and the battery inverter control is the responsible for keeping the frequency close to 50Hz.

The Inverter control scheme shown on Figure 34 has a different objective than the control shown on Figure 29. Firstly, the analysis done on section 4.6 assume that the batteries are used to cover the variations of power demand whereas the generators operate at a mean calculated by the approaches. Moreover the governors are responsible to control frequency, the AVR are responsible to control voltage and the battery inverter controls

the active and reactive power required from the batteries, this power control also helps on reducing the frequency and voltage variations, even though it was not designed for it.

The control shown on Figure 34, has full responsibility on the frequency control, since there are no governors, on the other hand, voltage control is divided between the average voltage regulator and the battery inverter control. To do the frequency control, a delta frequency between the measured frequency and 50 Hz is multiplied by a frequency gain γ_f , it is divided by $1.5 * V_d$ resulting in I_{dref} that is subtracted by $I_{dmeasured}$. The result of this subtraction pass through a PI control that integrates the error. To create a reference signal in the d axis, the output of the PI control is summed to the $V_{dmeasured}$, subtracted by the multiplication of the $I_{qmeasured}$ by $\omega * L_{grid}$, and then multiplied by $2/V_{DC}$. ω comes from $2 * \Pi * frequency$ and the measured signals on d and q axes are obtained by measuring voltage and frequency on abc axes and transforming them using the park transformation to the dq axis. Moreover frequency measured is obtained by using a Phase Locked Loop (PLL) that measures frequency and angle from a signal on the abc axes.

Figure 34 – Battery Inverter Control Scheme for Optimal Point.

To do the voltage control, the steps are almost the same but on the q axis, a delta voltage between the measured voltage, in pu, and 1 pu is multiplied by a voltage gain γ_v , it is divided by $1.5 * V_d$ resulting in I_{qref} that is subtracted by $I_{qmeasured}$. The result of this subtraction pass through a PI control that integrates the error. The difference between d and q axes control comes here, to create a reference signal in the q axis, the output of the PI control is summed to the $V_{qmeasured}$, summed by the multiplication of the $I_{dmeasured}$ by $\omega * L_{grid}$, and then multiplied by $2/V_{DC}$.

The reference signal in d and q axes are then combined and are transformed back to abc axes, the signal on abc axes is sent to a PWM that generates a signal to control the battery inverter.

The values of PI control for the inner loop and of L_{grid} were determined firstly using the method shown on [71]. After that, the values of γ_f , γ_v and of the PI control for the

upper loop were obtained by an iterative method.

4.7.1 Frequency and Voltage analysis for generators operating at fixed points

As said before the following results contemplate the operation of the generators at fixed points closer to the diesel generator optimal point, the points tested were chosen based on the investigation of the diesel consumption curve shown on Figure 25, 0.8 pu and 0.9 pu.

As can be seen from Figure 35, the period on which the PSV is pursuing the loading in port mission, requiring a lower amount of load from the generators, is used to charge the batteries in both operational points. From 0 to 30 seconds in both analysis, 0.8 and 0.9 pu, there is only one diesel generator providing power to the system, as can be seen the battery charges more when the generators operate at 0.9. At 30 seconds the load demand starts to ramp up, this increase on load demand lasts until 42 seconds, moment that the loads achieve the maximum demand required in the laden voyage, which is the worst case for frequency and voltage control. From 30 to 42 seconds the batteries provide power to the system to keep the frequency steady at 50Hz, when we compare the frequency data of the Figure 35 to the Figure 26 we can see that this power injection reduces the variation on frequency, this power injection has a considerable reflection on the state of charge of the battery that reduces during this period. From 42 to 80 seconds, as mentioned before the ship is pursuing the laden voyage, as can be seen from the graphic of battery active power during this period operating the generators at 0.9 pu cover the demand required from the loads and the battery is slightly charged, negative value on power shows that, on the other hand operating the diesel generators at 0.8 pu is not enough to cover the load demand, in this case the battery also provides power, maintaining the frequency at 50 Hz, it can be seen from the battery active power curve on which the levels for the 0.8 analysis are positive, that represents a discharging of the battery also shown on the battery state of charge curve.

The battery used on this analysis as said before is represented by a voltage source in series with a resistance, it does not have limit on power and the state of charge was modelled integrating the power provided from the batteries through the period of the simulation. The maximum capacity of the battery is 80 MWs and in both cases the battery started with 51% that represents 40.8 MWs of energy available during the simulation. During the simulation the battery reaches a maximum state of charge around 72%, when the generators operate at 0.9 pu, this configuration also leads to a final state of charge of 51%. On the other hand when operating the generators at 0.8 pu, leads to a maximum energy about 66%, at the end of the simulation the state of charge reaches 14%.

Figure 35 – Generator, Load and Battery Active Power and Frequency Results. The dashed line on frequency results means the limits of the PN-IEC-60092-101 for frequency.

Analysing frequency and voltage on Figures 35 and 36 can be seen that the frequency varies between 49.85 Hz and 50.15 Hz a maximum variation of 0.30%. Furthermore, voltage level varies between 1.009 and 0.991, a maximum variation of 0.9%. These upper and lower voltage and frequency obtained by the simulations are far from the limits imposed on the PN-IEC-60092-101, shown on Table 3 and marked on both figures as blue lines.

Table 7 cluster the data of consumption for cases with the bus-tie opened and closed mentioned on section 4.5 with the isochronous control, these cases that do not have a battery connected are compared to cases on which the bus-tie is closed and the generators

are kept operating at their optimal point, in these cases the batteries are connected to the grid and the generators are kept at 0.8 and 0.9 pu.

Figure 36 – Generator, Load and Battery Reactive Power and Voltage Results. The dashed line on voltage results means the limits of the PN-IEC-60092-101 for voltage.

From Figure 24, we can see that the bus-tie mentioned is shown in blue. As can be seen from Table 7 the operation with the bus-tie closed already reduces in 1.62% the diesel consumed, the CO_2 and the NO_x emitted. Keep the generators steady at 0.8 pu and 0.9 pu with the help of the batteries increases its reduction, reaching 5.97% for the generators operating at 0.8 pu and 6.48% for the generators operating at 0.9 pu. It could be foreseen from the analysis of the diesel consumption curve shown on Figure 25.

The third column of table 7 shows the results of the sum of the diesel consumed during the whole simulation (80 seconds) to the diesel spent to charge the batteries until its initial SoC (20.1%) as can be seen when we sum the diesel amount necessary to charge the battery, the operation spends more diesel than the operation with bus-tie opened. The fourth column of table 7 shows the outcomes of each case compared to the basis case, bus-tie opened, when the initial and final battery SoC are considered, both SoC are converted to diesel, taking into account that to produce this amount of energy was used one diesel generator operating at its optimal point, doing that if the battery SoC increases during the operation, the delta diesel between initial and end of the operation is then subtracted from the diesel consumed during the operation, on the contrary if the battery SoC decreases, the delta diesel is then summed to the diesel consumed during the operation. This approach was assumed since the higher the battery SoC the longer the period of time that the diesel generator can remain disconnected saving diesel in a future operation.

Table 7 – Diesel Consumption - Negative values represent an increase of consumption

Case	Reduction on Diesel Consumed (liters)	Reduction on Total Diesel Consumed battery charge + operation (liters)	Reduction on Total Diesel Consumed battery SoC (final-initial) + operation (liters)
Bus-Tie Opened	–	–	–
Bus-Tie Closed	13.91%	13.91%	13.91%
Generators at 0.8 pu	17.72%	-1.17%	4.24%
Generators at 0.9 pu	18.16%	-0.93%	17.86%

Table 8 – CO_2 and NO_x Emissions - Negative values represent an increase of emission

Case	CO_2 reduction (%)	NO_x reduction (%)
Isochronous Bus-Tie Opened	–	–
Isochronous Bus-Tie Closed	13.91 %	13.91%
Generators at 0.8 pu	17.72%	17.72%
Generators at 0.9 pu	18.16%	18.16%

Table 8 resumes the results of emission for all the cases. Since the CO_2 and the NO_x emitted are calculated by a relation between $kg_{CO_2}/Liters_{diesel}$ and $kg_{NO_x}/Liters_{diesel}$ the percentage of emission reduction for both gases follow the results shown on first column of table 7.

Discussion of the Results and Future Works

This chapter aimed to comprise the results of different analysis of the ship electrical power system, it started showing on section 4.5 that the discussions on operating with the bus-tie opened or closed must continue since there is a considerable gain in operating with the bus-tie closed, this gain should be also followed by the safety that ships have when operate with the bus-tie opened, this gain could be higher if the DP operation was analysed, it can be a future work to be performed when the international societies firm the requirements to run the DP operation with the bus-tie closed. As sections 4.6 and 4.7 presented before batteries can help to control or even take full control of frequency, moreover batteries can help to reduce diesel consumption and GHG emissions by keeping the generators operating closer to their optimal point, it is reinforced in 4.6 by showing that using batteries in peak shaving may not save diesel if the generators are operated with low load.

Looking for frequency and voltage is shown in 4.6 that the strategy adopted to increase the load demand also influences the variations of frequency and voltage. It can be seen that the washout filter approach presents the best results.

Finally, in 4.7 is shown that there is a considerable reduction of diesel consumption and GHG emission by operating the diesel generators closer to their optimal point. Moreover it is shown that operate the diesel generators at 0.9 pu can lead to a higher reduction if we consider that the energy stored on the battery can be used to disconnect one generator and then save diesel.

Future works can be dedicated to perform the same analysis to other ships that have a higher load demand. Another study can be done on substituting the AC grid to a DC grid, it can integrates better the batteries and can also helps to save diesel since variable speed engines does not have to control frequency, running at their optimal speed that provide power enough to meet the load demand. Moreover the curve of fuel consumption for variable speed engines have a lower variation range, it also helps on operation that

requires substantial variations of load. Substitution of diesel engines per dual fuel engines or per gas turbines are also fields of study that demand more deepening.

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