Hardware-In-Loop (HIL) platform for Electric Hybrid Power System Testbeds in the Maritime Industry

A Real Time Simulation Study
of the Proposed Marine Hybrid Ship

SET3901: Master Sustainable Energy Technology

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Hardware-In-Loop (HIL) platform for Electric Hybrid Power System Testbeds in the Maritime Industry

A Real Time Simulation Study of the Proposed Marine Hybrid Ship

by

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Preface

I am ecstatic to finally present this master thesis, thereby marking the end of my study of Sustainable Energy Technology, at the Delft University of Technology, Netherlands. The master of Sustainable Energy Technology has given me a sound foundation into understanding the opportunities and complexities of the integration of sustainable energy technologies into our everyday lives.This study has piqued my curiosity into the field of sustainable mobility and hybrid power systems that accelerate the transition from fossil fuel powered systems to clean energy systems. I would like to express my gratitude to Alewijnse Netherlands B.V for the internship opportunity and support throughout the internship. I would also like to express my gratitude to ir. Zoran Malbasić and ir. Matthijs Mosselaar at Alewijnse for their supervision and support throughout the internship. Learning from their experiences, feedback and additional learning in new fields of electrical engineering was truly amazing. Their continued support during challenging times of this thesis is greatly thanked. Furthermore, I would like to thank and acknowledge Mischa Habermehl (Team Lead Hybrid Solutions) for facilitating this collaboration with TU Delft. At the TU Delft, I am indebted to Dr.ir Zian Qin, for his supervision, advice and support throughout the course of this master thesis. Finally, I would like to extend my deepest gratitude to my parents Dr. Ajith Kumar Arayambath Kunhiraman Nair and Dr. Rashmi Naledath Palat for their unwavering support throughout the course of the my academic journey. This thesis is an amalgamation of an unnumbered collection of simulations, debugging cycles and parameter tuning on Typhoon HIL in addition to research, analysis and reflection. I hope that the findings of this thesis encourages further research and development, in sustainable energy technologies, to accelerate decarbonization in the transportation sector. I look forward to the new challenges in the evolving landscape of sustainable transportation.

Akhil Ajith
Delft, August 2024

Abstract

The research is conducted via collaboration between Alewijnse Netherlands B.V and the Delft University of Technology, Netherlands. The objective of this work is to verify the techno-economic feasibility, of a proposed hybrid marine vessel configuration. This proposed hybrid solution now requires an upgraded Energy Management System, to efficiently make use of the distributed energy resources on the grid. Verification of these results are conducted using the Typhoon Hardware - in - Loop (HIL) platform, to create a Digital Twin of the proposed hybrid marine vessel. The designed digital twin, with modified EMS control, is specifically aimed to optimize vessel operations in the DP2 mode. The designed EMS control ensures the vessel operates it's diesel generators at their optimal loading points, in combination with the battery energy storage system. This operation effectively reduces fuel consumption, reduces maintenance costs for generators and green house gas emissions. The findings of this research contributes to the field of green ships and marine industry decarbonization.

Keywords: Hybrid Vessel, Digital Twin, Hardware in Loop Simulation, Energy Management System, Green Shipping, Typhoon HIL, DP2.

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
AES	All Electric Ships
BESS	Battery Energy Storage System
DC	Direct Current
DER	Distributed Energy Resource
DG	Diesel Generators
DNV	Det Norske Veritas
DNV GL	Det Norske Veritas Germanischer Lloyds
DoD	Depth of Discharge
DP	Dynamic Positioning
DP2	Dynamic Positioning 2
EC	European Commission
EES	Electrical Energy Storage
EoL	End of Life
ESS	Energy Storage System
EMS	Energy Management System
EU	European Union
EUR	Euro
EU ETS	European Union Emission Trading System
GHG	Green House Gas
HIL	Hardware-In-Loop
IMO	International Maritime Organization
LNG	Liquefied Natural Gas
MGO	Marine Gas Oil
ML	Machine Learning
MTBO	Minimum Time Before Overhaul
NEDC	New European Driving Cycle
RES	Renewable Energy Sources
ROI	Return on Investment
SPBT	Simple Payback Time
SDG	Sustainable Development Goal
SFOC	Specific Fuel Oil Consumption
SoC	State of Charge
SoH	State of Health
SPC	Standard Processing Core
UN	United Nations
UNECE	United Nations Economic Commission for Europe
U.S	United States
USD	United States Dollar
VFD	Variable Frequency Drive

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1 Introduction

The maritime industry is believed to be the backbone of economic development and trade relations between nations for several years [1]. It is believed that nearly 80% of global trade is dependent on the maritime sector for transport [2]. The International Maritime Organization (IMO) estimates that the shipping industry consumes 300 million tonnes of fuel annually [1]. This large fuel consumption also leads to green house gas (GHG) emissions on an unprecedented scale. The Fourth IMO GHG Study 2020, estimates that GHG emissions that include carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), all expressed in CO_2.eq, have risen. Their study concluded that emissions have risen at 9.6% as of 2018, when compared against their last study in 2012. That equals a total emission valued at 1076 million tonnes. Total CO_2 emissions have increased from 962 million tonnes as of 2012 to 1056 million tonnes as of 2018 [3]. Decarbonization of the shipping industry in tandem with other sectors is viewed as an important pathway to reduce environmental damage. It is believed that if no concrete measures are taken, CO_2 emissions are projected to rise by 50-250 % by 2050 [4]. The consequences of these emissions include and are not limited to rising sea levels, mass extinction of plant and animal species, increased frequency of natural disasters such as cyclones, heat waves, floods and pollution of natural resources among many others.

The IMO, in view of the consequences of the environmental damage and in support of the United Nations (UN) Sustainable Development Goal (SDG) 13, has adopted the 2023 IMO Strategy on Reduction of GHG Emissions from Ships. This strategy sets a framework that guides member states to their path of decarbonization of their shipping industries, fully considering short-term to long-term impacts, potential barriers and solutions. They also strive to establish a platform for technical collaboration, research and development [5]. Their main objectives include a reduction in carbon intensity of international shipping, as an average across international shipping, by approximately 40% by 2030. An additional ambition is the integration of zero or near-zero GHG emission technologies, fuels and/or energy sources in the range of 5-10% by 2030 [5]. Although there is significant pressure on the maritime industry to limit their fuel consumption and carbon emissions, it must be noted that the operation profile of these ships are very different. Nowadays, offshore vessels are required to perform several tasks such as transportation, critical operation such as the dynamic positioning, operation of cranes and other heavy load operations. Due to these varying demands from the vessel, the power plant needs to do well in several key performance criterion as stipulated below [4] :

1. Fuel Consumption
2. GHG Emissions
3. Noise Reduction
4. Propulsion
5. Manoeuvrability
6. Comfort due to minimal noise, vibrations and smell
7. Maintenance cost due to engine thermal and mechanical loading
8. Profitability of Investment

1.1. Research Objective

The objective of this research project is to evaluate the the feasibility of the proposed Marine Hybrid solution for a cable laying vessel at Alewijnse Netherlands B.V. This project is conducted in collaboration with Alewijnse Netherlands B.V, a leading maritime electrical integrator based in the Netherlands, for a master thesis at the Delft University of Technology, Netherlands. The "Cable Laying Vessel",takes part in underwater cable installations in different parts of the world. Cable Laying Vessels may also be used as a research vessel during periods of non-activity in the cable laying field. This Vessel is equipped with the dynamic positioning technology. Dynamic Positioning (DP) is an important technology that helps position the ship in uncertain waters and re-positions the vessel, to it's intended location coordinates when displaced by environmental forces. This is a critical operating mode as the vessel takes part in it's cable laying activities. Cable Laying Vessels also have the DP-2 class mandate to ensure redundancy requirements are met, in the event of failure of any component onboard the vessel. In order to verify the hybrid solution proposal, a digital twin of the proposed "Hybrid Cable Laying Vessel" is created on Typhoon Hardware-in-Loop (HIL), to extract simulation results in real time. In addition, an effective energy management system controller, is developed for the DP2 operation mode of the ship, such that the generators onboard operate at an optimal operating point. This ensures reduced fuel consumption and delaying the minimum time before overhaul (MTBO) for the Diesel Generators (DGs) and lesser GHG emissions.

1.2. Alewijnse B.V Netherlands

Alewijnse is one of the leading maritime electrical systems integrators in the Netherlands, with a wide range of technical solutions offered. These solutions include the fields of power conversion, electrical power distribution, switchboards and consoles, electrical installations, navigation and communication, process automation, audio/video & IT, vessel automation and safety & security systems. The sectors Alewijnse is part of include yachting, naval, dredging, offshore and industrial applications. Additionally, Alewijnse is involved with systems integration for non-maritime sectors that includes projects in access for clean water, air treatment plants, food processor technology and geothermal energy technology automation. Alewijnse's motto is to create value for their employees and customers, foster progress and development from the start to the very end of each of project.

Figure 1.1: Alewijnse Company Logo

Figure 1.2: The Bravo Eugenia yacht integrated by Alewijnse

1.3. Relevance of this Project to Academia and Industry

Alewijnse intends to integrate the proposed marine hybrid solution to the cable laying vessel as part of a request from the client. The expectation is that with the installation of two battery energy storage systems (BESS), there will be a reduction in the number of active diesel generators (DGs), that are required for redundancy during the DP mode. The operation of the DGs and BESS are optimized based on the fuel consumption graphs provided by the client, by means of an energy management system (EMS). The designed EMS operates such that the DGs operate at an optimal operation point that reduces fuel consumption and carbon emissions. Additionally, at this operating point, there is the opportunity to delay the maintenance time for the generators, which translates into large monetary savings. The BESS operates with a number of functionalities that include acting as a spinning reserve, assist in peak shaving, start/stop operation and load levelling. The EMS is responsible for the effective control and distribution of loads among the various energy sources to meet load demands of the ship. The EMS also needs to make these decisions keeping in mind the limitation of each energy source and operate them such that their lifetime can be maximized. Therefore, the designed control logic can help verify the feasibility of the proposed hybrid solution for the DP2 operation mode of the cable laying vessel and projected savings. The obtained results are evaluated and shared for discussion. This research finally acts as a stepping stone to decarbonization of the maritime sector. The designed EMS controller can also be applied on other vessels, with the required modifications specific to that vessel. Therefore the designed model is transferable and modular.

1.4. Research Objective and Questions

The goal of this master's thesis research project is to establish the answers to the following questions:

What is the most effective control mechanism such that the power demands of the vessel are met, keeping in mind the need to limit fuel consumption, carbon emissions and delay the maintenance schedule for the vessel? How can the BESS compliment the EMS to meet these requirements keeping in mind the limitations of the battery operation?

The **primary research question** that this research aims to find is:

How can the EMS of the proposed hybrid configuration of the vessel optimize the use of their energy sources?

The following sub-questions are proposed to assist in answering the primary research question

Sub Question 1: How can the EMS of the proposed hybrid configuration of the vessel, optimize the use of their energy sources?

Sub Question 2: How do the different operational profiles of the vessel impact the EMS's ability to efficiently make use of the distributed energy sources in the network?

Sub Question 3: How do the EMS's decisions optimize the operation of the vessel with its constraints such as the DG maintenance, fuel consumption minimization, carbon emission reduction and BESS maintenance?

Sub Question 4: What are the projected monetary savings that can be achieved from the proposed Hybrid Vessel Solution? Can this model be profitable?

1.5. Structure of Report

This report is structured in the following manner:

- **Chapter 2:** This chapter explores the literature and research and current trends and practices that have been employed for the field of optimizing hybrid vessels and vehicles. An analysis of different approaches conducted for simulations conducted on Hardware-in-Loop platforms and real time and preset time applications.

- **Chapter 3:** This chapter provides some insight into the vessel under study. The details and specifics that designated the requirements for the hybrid proposal are discussed.

- **Chapter 4:** This chapter provides some insight into the vessel under study. The use of the Typhoon Hardware-In-Loop (HIL) platform and it’s potential solutions for the vessel and other applications are discussed.

- **Chapter 5:** This chapter details the implementation of the designed EMS control scheme for the proposed hybrid vessel. The application of the control logic into Typhoon HIL for real time simulation result extraction is discussed.

- **Chapter 6:** This chapter takes into account tests conducted for the Hybrid Vessel in the Taiwan Strait and North Sea, using the provided operational loads data. This chapter shows how the actual marine hybrid solution would perform, during normal operations.

- **Chapter 7:** This chapter is focused on results and discussions. It explores the potential maintenance savings, fuel cost savings, offset carbon emissions and the profitability of the solution.

2 Literature Review

2.1. A brief perspective into the history of marine power systems

Historical records credit the earliest effort in marine vessel electrification to Moritz Hermann Jacobi. Mr.Jacobi created a system powering a DC motor by means of a battery in an experimental setup for small boats. However, this setup was rid with plenty of faults and as a result, the electrification of propulsion systems for vessels was delayed [6]. With the invention of the incandescent light bulb, the *SS Columbia*, a passenger and freight vessel, installed electric lighting units on the vessel in 1880. The system was regulated by the crew, wherein the intensity of light displayed would dictate the generator power output [6]. With these developments, the U.S Bureau of Navigation set guidelines for installation of electrical light bulbs on vessels. With time, there was the integration of electrical motors into the ship's powerplant for a variety of purposes including lighting, heavy machinery and naval defense applications. However, it is to be noted that most of these applications were based on the use of DC motors, owing to the fact that AC motors were still under development for these applications. In the year 1885, the German firm *Siemens and Halske*, built the *Elektra*, that could ferry up-to 30 people, and was powered by a 4.5 - kW motor and batteries [6].

With the advancement of AC powered motors and the closed core transformer, there was a trend seen with a shift towards the adoption of AC systems for marine vessels especially in the US and Germany. The key driving force behind this decision was that AC systems can be designed to be small and lightweight in comparison to the DC counterparts. The use of AC systems up-to a frequency of 400Hz was challenging due to the use of mechanical frequency converters at the time. In 1908, although the practicality of AC propulsion was demonstrated, the absence of modern power electronic control created complexities for operations. By the beginning of the twentieth century, Great Britain continued to develop steam power based drive systems with reduction gears, whereas the US focused upon the turbo-electric drive segment. The *USS Jupiter* was designed as a hybrid powerplant consisting of a diesel engine and steam powered turbine unit. With further development, it was noted that these vessels can be designed with simpler structures that occupy less space and their fuel savings improved in this hybrid configuration [6].

The advancement of electrical drives and power electronics have been a key driving force in the modern shipping propulsion transformation. Power electronic converters having dual functionalities, which is to operate as an inverter and rectifier, offered solutions to challenges faced with mechanical power conversion devices. By the 1980s, power electronic devices were exploited to maximize vessel performance and fuel savings. The British Vessel *Queen Elizabeth II*, was equipped using nine German *MAN* diesel generators to an all electric transmission [6]. The design was perfected such that the vessel could operate with just 7 generators and maintain its set design speed of 28.5 knots, while reducing fuel consumption by 35% [6]. By the twentieth century, diesel electric propulsion was the norm. There was also the introduction of LNG powered vessels and the development of nuclear powered steam turbine units as seen in submarines like the *USS Nautilus* in 1954. Vessels also began to have more complicated tasks such as the Dynamic Positioning Mode, which requires specialized power electronic converters for effective and timely operation [6].

With continued technological development and environmental concerns in mind, there is significant interest in hybrid powertrains for marine vessels. These powertrains are powered either via a gas turbine direct drive or by means of diesel generators that operate electric motors connected to the propulsion units.Lately, the inclusion of fuel cells and BESS technologies have advanced the drive to clean and alternative energy sources for the hybrid powertrain design.

2.2. Dynamic Positioning Mode For Marine Vessels

With limited sources of energy on land, there is the need to explore the oceans to meet global energy demand [7]. This is achieved by tapping into the energy available from offshore wind energy plants and oil fields. The construction and installation of these facilities is achieved with specialized construction cranes [7]. While operating the vessel in deep waters, there is the regulation to avoid using anchors to hold position of the vessel. For this reason, in order to maintain the vessel's position, it is equipped with thrusters, rudders and propellers, controlled by the Vessel's Dynamic Positioning (DP) system, against environmental disturbances [8]. The environmental disturbances endured by the vessel includes dynamic ocean and wave patterns and wind speeds, that can displace the vessel from it's intended location coordinates [8]. A vessel has 6 degrees of motion. They are namely Surging, Swaying, Yaw, Heaving, Pitch, Rolling [8]. However, the DP system can control only 3 horizontal axes namely the surge, sway and yaw [7]. The other components are used by the navigation system and antennas. The advantages of the DP system is mentioned below:

- Position and reposition the vessel to desired location coordinates, with a high degree of accuracy [8].
- It can offer the vessel operators control with a high degree of flexibility [8].
- Able to operate at large range of ocean depths [8].
- The DP mode works continuously to keep the vessel in it's intended location. This can prevent potential marine collisions that can result in environmental pollution. [8].

With use of propotional-integral-derivative (PID) controllers, the thruster control system can control the horizontal motion of the vessel. This control system was established in the 1970s and thus named the DP system [8]. The vessel consists of several position reference systems, gyroscopes and motion reference units. These sensors provide the necessary information such as the vessel speed, deviation and heading. The controllers and computer system make necessary calculations based on this data, to position and stabilize the vessel. An overview of DP Class set by Det Norske Veritas Germanischer Lloyds (DNV GL) is stipulated in the table 2.1

Table 2.1: DP Modes [9]

Mode	Specification
DP1	This class has no redundancy and is subject to risk in the event of a fault. The vessel will not be able to reposition if a fault occurs.
DP2	This class has redundancy requirements to be met. The vessel should be able to continue operations and positioning even if one generator or thruster or valve experiences a fault.
DP3	This mode is also resilient to fire hazards or flooding events in the watertight compartments. The vessel must be able to continue to operate and position despite these events.

2.3. Diesel Generators as the Power Source in the Grid

Diesel engines have been the backbone of marine vessel powerplants over the last few decades. It is estimated that more than 90% of large commercial vessels employ diesel engines as the prime movers for propulsion [10]. The reasons for the diesel engine to dominate this sector is due to it's ability to meet market demands, provide high power capacities, make use of low grade fuel oil, their reliability and durability over long operation [10]. The first step during shipboard power system analysis is the electrical load analysis, that dictates the sizing of the generators. This is a rigorous process that includes load factor analysis, day and night load analysis and statistical analyses to suitably size the powerplant [11]. Critical equipment onboard the ship that includes the pump network, navigation system and Dynamic Positioning are especially investigated in different operational modes to extract the ideal design for the electrical powerplant. In addition, power line losses, loading limits, generator capacities and financial constraints decide the final configuration [11]. One of the main drawbacks of this approach is that the generators are often operated at low loading points [11]. This is because, the vessel load demands are never the same. They constantly change, depending upon how critical their operation is, and the sea and weather conditions that keep changing.

Continued operation of diesel generators at low loading points results in poor fuel economy operation and expensive maintenance requirements [12], [13]. At low loading of DGs, incomplete combustion of fuel oil occurs. In this process, the air-to-fuel mixture ratio may contain more parts of air than fuel. The result of this process is that some fuel oil is left unused and condenses to form carbon deposits, over the surface of the engine's mechanical components. This unfavorable phenomena is termed as "wet-stacking". In addition to this undesirable effect, at low loading points of DGs, the emission factor of this partly burnt fuel mixture is much higher than the fuel mixture burnt at higher loading points. This results in greater GHG emissions [12], [13]. Therefore, the consequence of this phenomenon is frequent and expensive maintenance service requirements, to extend the lifetime of the diesel generators.

Figure 2.1: Effect of Wet Stacking on the Diesel Engine's Piston [12]

Additional consequences include increased exhaust smoke, presence of fuel traces in engine oil and wear of turbochargers, resulting in oil leaks. High pressure is experienced in the gearbox and blowby and hardening of cylinder liners are common occurrences at low loading points. In the long-run, continued operation at these load levels, would result in severe damage to critical components of the diesel generators. The expected outcome of this situation is expensive maintenance processes and replacement of generator components, alongside excessive fuel consumption and GHG emissions [14].

2.3.1. Pros of Using Diesel Generators

The advantages to using DGs in meeting the marine vessel's load demands are summarized as follows:

- High Power Capacity and occupies a considerably lower space for installation.
- Ability to use different fuel types, that can potentially reduce costs for the operator.
- High degree of reliability and resilience.
- Offers long duration of operation, before having to undergo maintenance.
- Relatively mature technology, given continuous development over the past few decades.

2.3.2. Cons of Using Diesel Generators

At the same time, DGs experience certain challenges that might suggest their use to be undesirable. They are summarized below:

- At low load demands, against the rated capacity of the DG, it operates inefficiently. It experiences the problem of wet stacking.
- At low load demands, fuel consumption efficiency is low, resulting in large fuel consumption for the energy delivered.
- Wet-stacking events result in carbon deposits over the engine, corrosion and erosion of the engine's mechanical components. This will result in costly maintenance procedures and reduced operational hours for the DG.
- DGs emit GHGs which harm the environment. With the European Union Emissions Trading System (EU ETS) coming into force for the maritime sector, it is necessary for vessel operators to limit emissions as much as possible.
- At low loads, combustion efficiency is on the lower end, creating large scale emissions for the limited energy it delivers.

2.4. Optimizing the Maintenance Schedule and Fuel Consumption of Diesel Generators

This section explores the maintenance schedule and fuel consumption for diesel generators, with respect to the loading percentage of the DG. In order to extract higher operating efficiencies and reduce maintenance costs, the load factor is an important parameter.

An often ignored factor in the use of diesel generators is the associated costs of maintenance, which can account for up-to hundreds of thousands of euros each year [15]. The formulation of the maintenance costs of the diesel generators can be further divided to three components as stipulated by equation 2.1. The operational and maintenance costs ($C_{O\&M}$) are the summation of the preventive maintenance costs (C_{PM}), operation costs (C_O) and the corrective maintenance costs (C_{CM}) [15].

$$C_{\text{O\&M}} = C_{\text{PM}} + C_{\text{O}} + C_{\text{CM}} \tag{2.1}$$

The preventive maintenance costs are costs that are the result of relatively simple maintenance procedures such as the cleaning of nozzles and replacement of transmission belts. The preventive maintenance procedures are relatively short and recommended by manufactures in scheduled time intervals throughout the year. The operation costs are the costs that are associated with the replacement or refurbishment of certain components of the generator such as oil filters and lubricants. The corrective maintenance costs are the costs that are the result of the several thousand hours of operation of the generator. The corrective maintenance costs depend upon the size of the generator, the load profile of the vessel and the dispatch priority used by the vessel operator [15]. The duration of the corrective maintenance procedures determine the minimum time before overhaul (MTBO) [15]. The authors of [15], established a mathematical formula 2.2 to approximately estimate the MTBO based upon the DG loading factor. The coefficient θ^i corresponds to the DG loading factor, whereas the the value of b_i, is detailed by table 2.2.

Table 2.2: MTBO Curve Coefficients [15]

b_n	Value
b_0	1040.898
b_1	3.429×10^4
b_2	1.660×10^4
b_3	4.971×10^4
b_4	-3.226×10^5
b_5	-5.504×10^5
b_6	2.803×10^6
b_7	-3.714×10^6
b_8	1.152×10^6

$$MTBO = \sum_{i=1}^{8} b_i * \theta^i \tag{2.2}$$

The minimum time before overhaul (MTBO) curve was derived based on the assumptions that the MTBO is dependent upon the average load factor and that the overhaul cost is roughly half the cost of investment into the diesel generator. From this curve, we can approximate that the minimum time before overhaul is delayed the most when the average loading factor is placed between 50% and 80%. The frequency of maintenance overhauls in general, increase as the average loading factor the diesel generator is below 50% or greater than 80%.

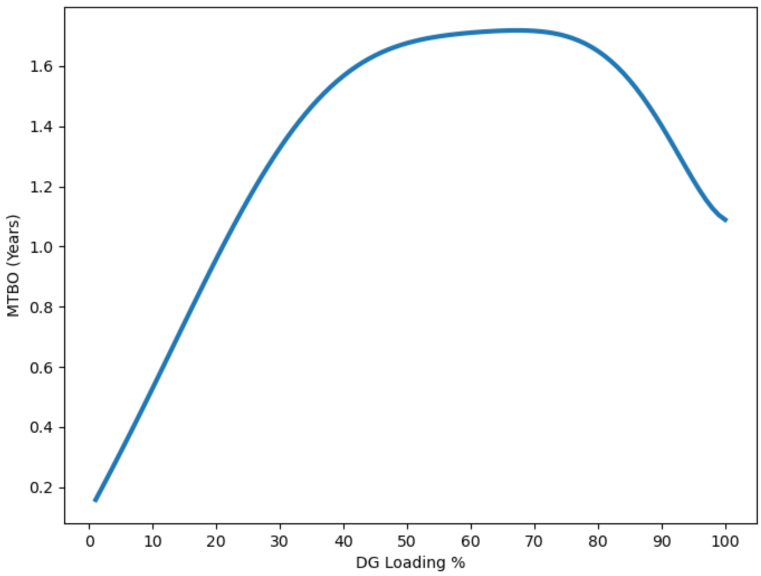


Figure 2.2: The Minimum Time Before Overhaul as a function of DG. Loading %

The authors of [15], based upon the the assumptions that they had made, established a mathematical formula to approximately estimate the corrective maintenance costs (C_{CM}), based upon the average loading factor of the DG. The equation 2.3 represents the approach to estimate these costs. N_h

represents the daily operation hours, C_{DG} represents the cost of the diesel generator and MTBO(ϕ) represents the MTBO at the average loading factor.

$$C_{\text{CM}} = \frac{365 \cdot N_h \cdot 0.5 \cdot C_{\text{DG}}}{1.3 \cdot \text{MTBO}(\phi)} \tag{2.3}$$

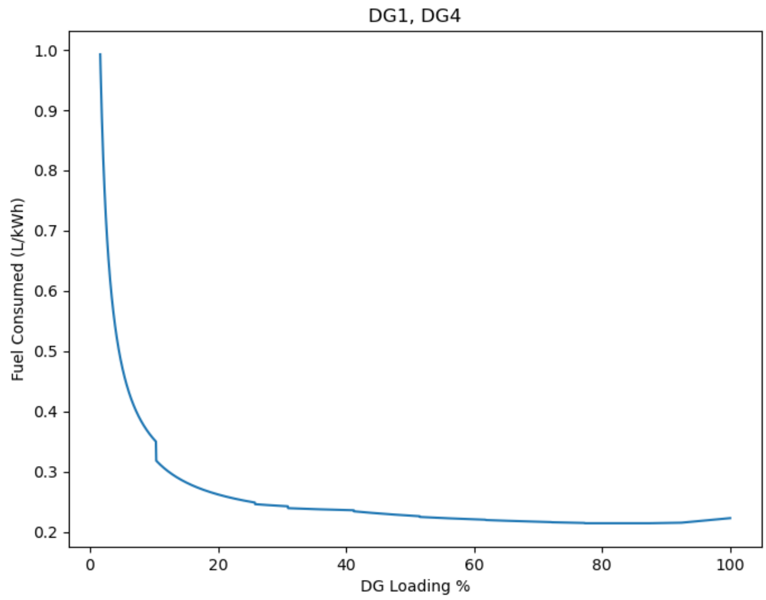


Figure 2.3: 1912 kW Diesel Generator SFOC Curve

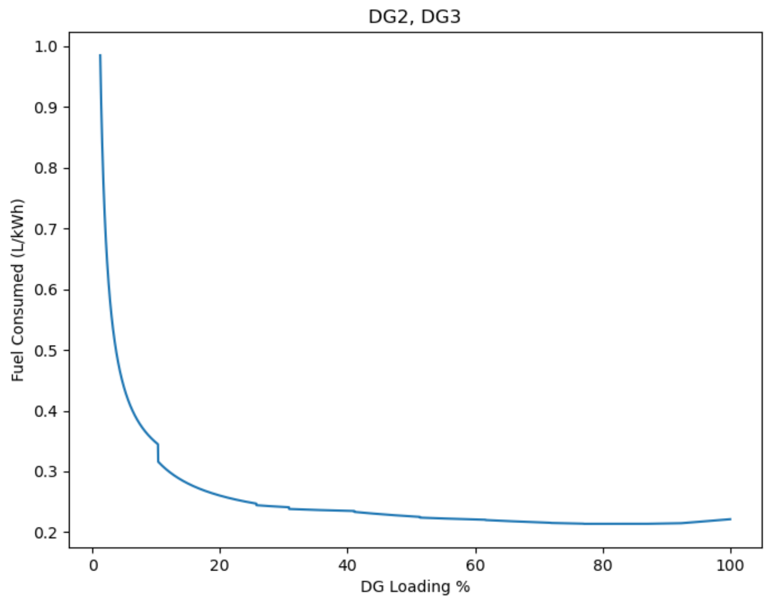


Figure 2.4: 2560 kW Diesel Generator SFOC Curve

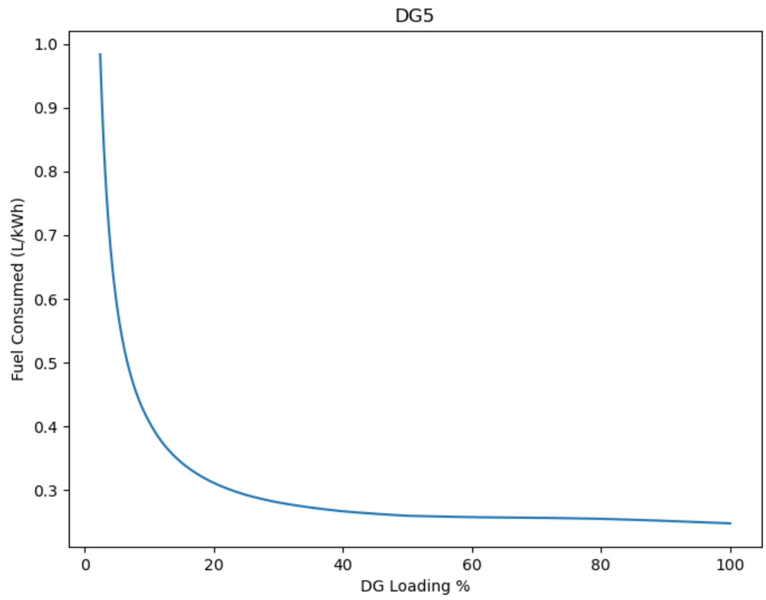


Figure 2.5: 1370kW Diesel Generator SFOC Curve

The specific fuel oil consumption of the diesel generators decrease as the loading percentage of the DG increases. The SFOC has a direct impact on the operation of the DG, the environmental impact of using the DG, the cost of operation and maintenance and the reliability of the DG in the longrun. A lower SFOC indicates higher fuel consumption efficiencies and lesser expenditure towards the maintenance and service of the DG components. Higher fuel consumption efficiency implies reduction in CO_2 emissions, better internal combustion processes and lesser frequency of wet-stacking events.

2.4.1. Potential solutions to the Challenges of using Diesel Generators

One of the main challenges DGs face in their operation is the phenomena of wet stacking. From the findings above, it is clear the phenomena of wet-stacking is undesirable. There can be increased frequency of maintenance schedules to replace damaged components and high fuel consumption, for a limited amount of energy delivered by the DG.

One of the solutions to this problem is to make use of a load bank in the form of a resistor. This controlled resistor, along with operational loads, loads the DG to an optimal operating point, creating additional heat energy. However, there is the additional fuel wastage and the problem of inability to effectively implement this solution in parallel DG operational configurations [12]. Alternatively, hybrid configurations with energy storage systems (ESS), can reduce low load dependence on the diesel generators. The ESS will have additional operations such as load levelling, peak shaving and operation as a spinning reserve, to ensure that the DGs operate only in the region of high efficiency [13]. Therefore, this solution can solve two possible problems faced by the DGs. It can reduce maintenance costs and reduce fuel consumption for the energy delivered by the DG. At this optimal loading, the DG delivers more energy at a slightly lesser fuel consumption.

2.5. Hybrid Vessel Configuration

Marine vessels running with DGs on their own are subject to challenges as explained in the previous sections. Therefore, in order to overcome the challenges with fuel oil consumption, emissions and maintenance cost minimization, hybridizing the vessel can be a suitable alternative. With 2 or more energy sources of different types connected to the grid, their differing operational requirements can be optimized to solve this problem.

The modern day application of hybrid configurations to electrical powerplants can vary depending upon the application, target industry and role of the powerplant. When assessing the types of hybrid configurations for vessels, there are predominantly 3 types. They are Hybrid Mechanical Propulsion, Hybrid Electrical Propulsion and Hybrid Electrical - Mechanical Propulsion [16].

- **Hybrid Mechanical Propulsion** : In this type of propulsion, power supply is achieved using multiple mechanical engines that are linked through a common gearbox or to provide thrust directly to the propeller. Typical engines in this configuration are diesel and gas- turbine - prime movers [16].

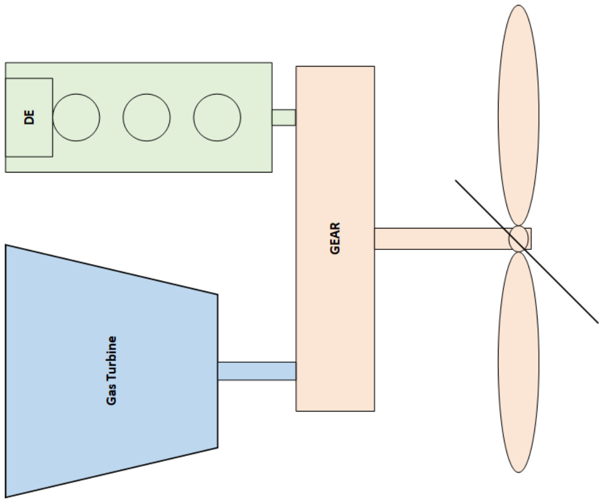


Figure 2.6: Hybrid Mechanical Vessel Powertrain

- **Hybrid Electrical Propulsion** : This type of propulsion is achieved by providing electrical power to the propeller shaft. This electrical power can be supplied by multiple sources such as diesel generators, batteries, fuel cells and capacitors. These components are generally operated in combination. With the advanced power electronic converters, it is possible to operate a grid having AC and DC powerplants [16].

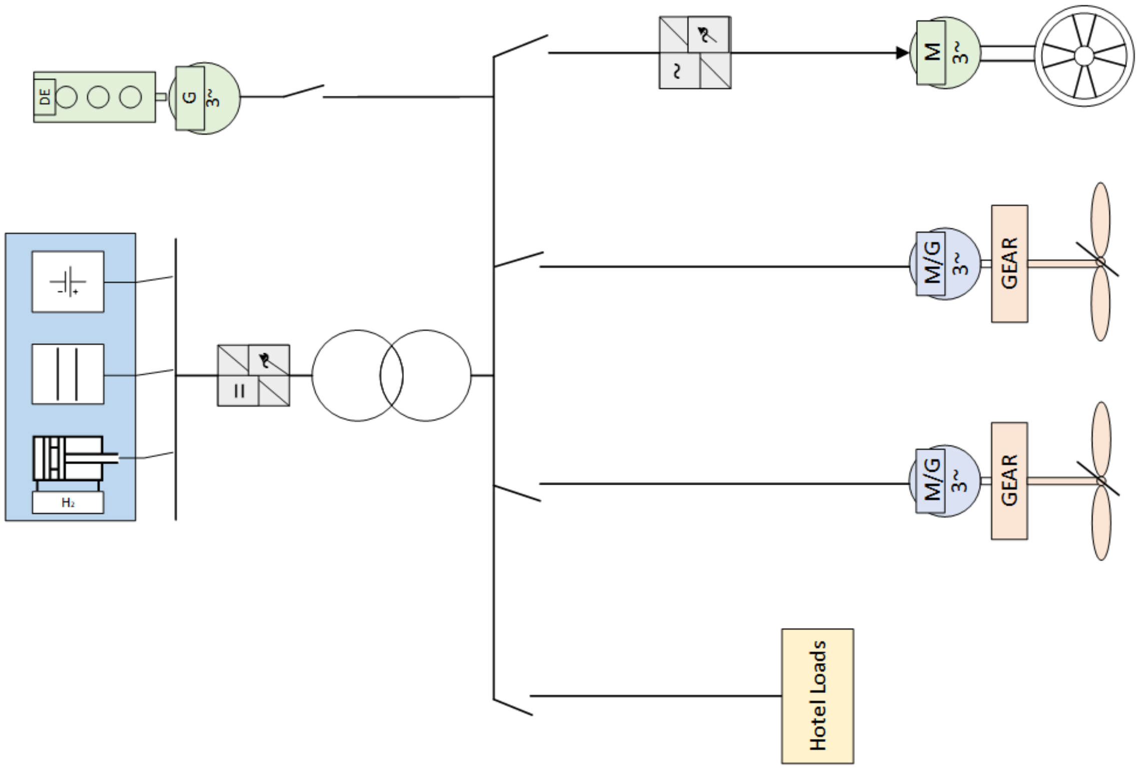


Figure 2.7: Hybrid Electrical Vessel Powertrain

- **Hybrid Electrical - Mechanical Propulsion** : This configuration uses a combination of mechanical and electrical propulsion units for the vessel interlinked to eachother. A vessel of this type would typically have a diesel generator directly connected to the propulsion units for sailing. Later on, it may switch over to electrically power the thruster units for dynamic positioning [16].

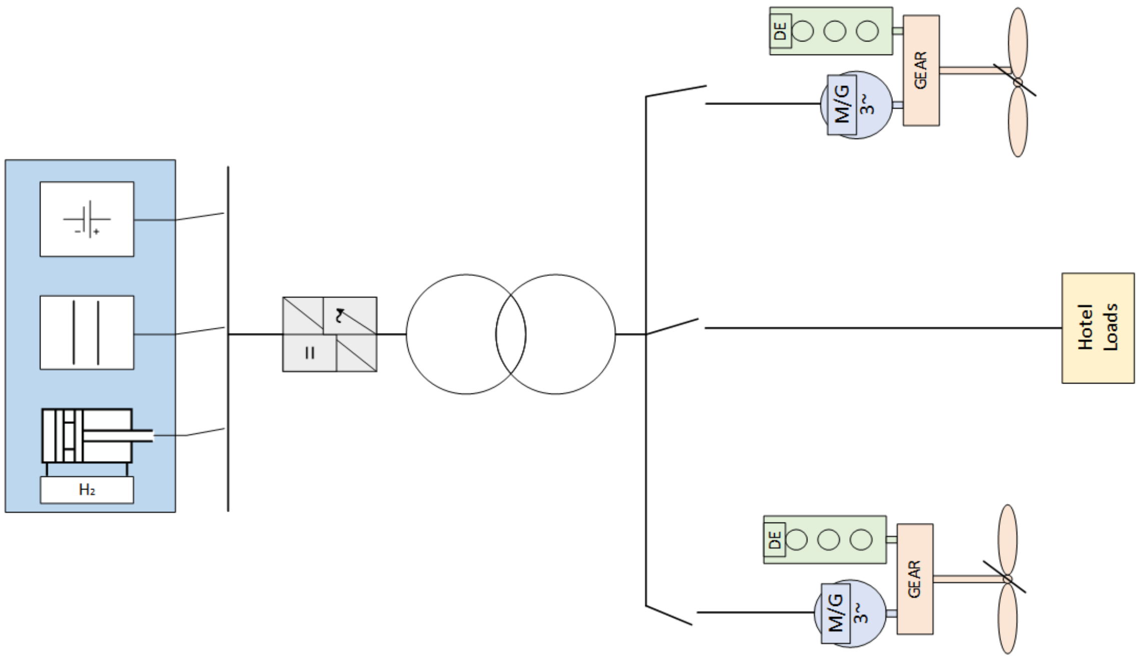


Figure 2.8: Hybrid Electrical Mechanical Vessel Powertrain

2.6. Application of Battery Energy Storage Systems for Marine Powerplants

As discussed earlier in chapter 1, it is clear that the shipping industry is a major source of GHG emissions such as CO_2, nitrous oxides NO_X and sulfur oxides SO_X. With new IMO emission targets, regulations and energy efficiency mandates, vessel builders are experimenting with different technologies to meet these criteria [17]. With the development and maturity of power electronic devices for a wide range of applications, All Electric Ships (AES) have now become possible. In addition, the development of energy storage technologies have paved way for the conversion of electrical energy to an alternative form for storage, and back to electrical energy [17]. It is found that AES ensure better design of the vessel, are more efficient and perform better in terms of the fuel economy [18]. Furthermore, the integration of electrical energy storage systems add to reliability and enhance redundancy requirements of vessels [17].
The advantages of the BESS are defined in figure 2.9. Some of the main advantages include, but are not limited to the following [18], [19]:

1. The BESS provides fast energy delivery response and peak shaving activities.
2. The BESS network makes lesser noise.
3. Installation of BESS can help integrate renewable energy sources (RES) into the network. Technologies that can be added include solar panels, wind turbines and fuel cells.
4. Energy efficiency of electrical energy storage system are on the higher end, compared to their fossil fuel powered counterparts.
5. The operation of the BESS as a spinning reserve can serve as the sole energy source during generator fault events.
6. The additional energy source available in the network adds to the redundancy requirements of the vessel for it's various critical and non-critical operating modes.
7. The operation of BESS in place of diesel generators, reduces fuel consumption and GHG emissions.
8. The technology has relatively lower maintenance requirements and costs over it's lifetime.
9. The BESS ensures optimal loading and operation of diesel generators.

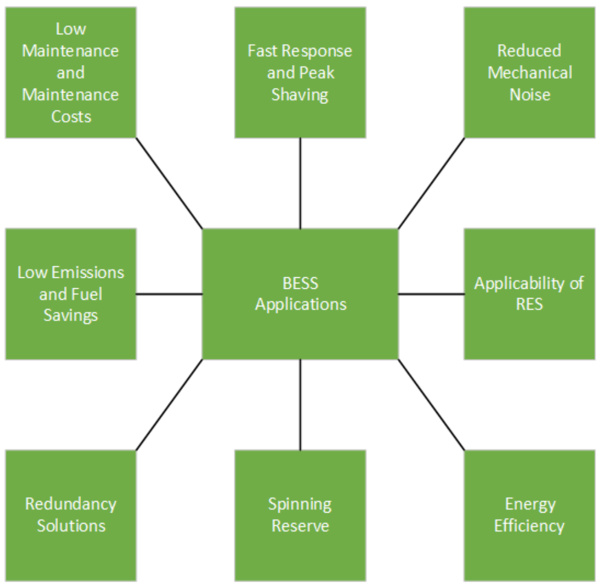


Figure 2.9: Advantages of Battery Energy Storage System

Some of the potential drawbacks of BESS technology are mentioned below:

1. Limited energy density. In order to have sufficiently large BESS capacity, the space required to install batteries can be quite large. This can be quite challenging for vessels that do not have the space.
2. BESS technologies are subject to calendar ageing and can degrade relatively quickly.
3. BESS technologies are yet to reach technological maturity for long duration operation.
4. This technology has high capital investment expenditures, which can take a long time before the investment becomes profitable. This is dependent on several factors within the BESS and outside the BESS, such as the EMS control.

2.7. Battery Degradation From the DoD and C-rate Perspective

The use of BESSs to reduce energy costs in terms of reduced fuel consumption has been worked upon in several applications. Increased cycling of BESS can offer monetary gains from the process, however, the higher the depth of discharge and C-rate, the higher the risk of fire and speed up of the aging process [20]. The depth of discharge refers to the capacity of the battery that is discharged as useful energy against it's overall capacity. The depth of discharge (DoD) also influences the BESS' state of health (SoH) and end of life (EoL) characteristics [20], [21]. If the BESS undergoes deep cycles, there is the increased risk of internal cell level stress, decreased energy storage capacity and reduced lifetime [20], [21]. Experiments conducted by the authors of [21] on LFP batteries, confirm that cell level internal resistance, increases with increasing depth of discharge. They also found that the internal resistance increases at a staggering rate of 132% for 100% DoD. The internal resistance was found to increase at 126%, 119%, 116%, 112% for 80%, 60%, 40% and 20% DoD respectively [21]. The limited BESS lifetime is a critical factor that needs to be considered for optimized energy dispatch, due to high costs of battery technologies. Based of the research conducted by the authors of [20], [22], it is found that the ideal DoD is in the range of 60 to 70 for batteries with SoH ranging between 80-90 and 90-100 respectively.

Additionally, the C-rate is defined as the rate of charge or discharge of the BESS as a measure of it's capacity. The C-rate heavily influences the lifetime and overall performance of the battery, given that it directly influences the rate of chemical reactions inside the cell [23]. At high C-rates, there is a high rate of transfer of energy, resulting in heat generation and mechanical stresses and strain inside the battery cell structure. The high C-rate and internal resistance in the cell, result in increased Joule losses, causing high surface temperature [21]. The high internal resistance is due to the solid electrolyte interface (SEI) deposit forming cracks in the cell [21]. This layer continues to thicken over the years, thereby increasing the internal resistance. This results in shortening of the BESS lifetime [21], [23]. Therefore, the C-rate along with the DoD are crucial factors that determine the integrity and longevity of the BESS operation and performance. The authors of [21], [23], found that lower the C-rate the better for BESS integrity and increasing lifespan. Tests on LFP batteries by [21], found that at high constant C-rates, the number of cycles available for discharge decline. On testing the C-rates of 1C, 5C,10C and 15C for a 100% DoD at room temperature, the capacity of the battery significantly changes. They found the lifetime of the battery to be 2900, 2060, 1100 and 560 cycles respectively. So in conclusion, the higher the C-rate, the faster the decrease in capacity.

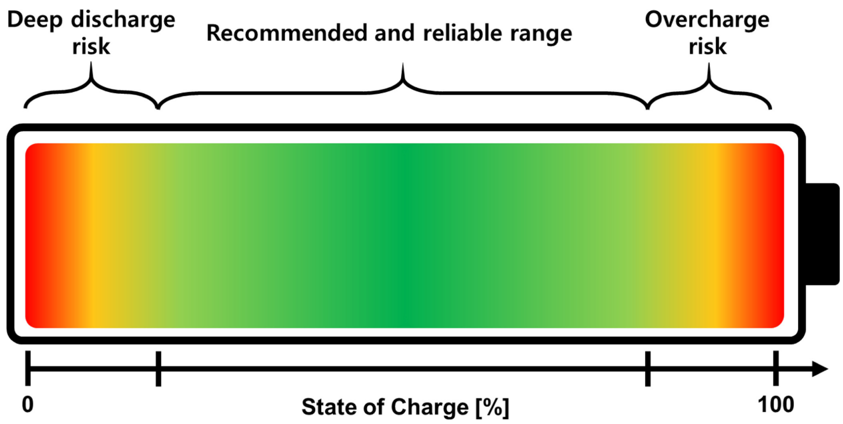


Figure 2.10: BESS Lifespan in view of SoC [20]

2.8. Hybrid Vessel Energy Management Systems

The integration of Battery Energy Storage Systems (BESS) with diesel generators (DGs), requires effective energy management strategies, in order to realize fuel savings, emissions reduction and integrity of the electrical powergrid [24]. The energy management system is responsible for meeting energy demands in the powergrid, while sharing these energy demands among the different distributed energy resources (DERs), while minimizing fuel consumption and GHG emissions. There are several energy management strategies that can be applied for road based hybrid electric vehicles. However, the same application into the maritime sector remains limited [24]. There are certain differences between road based hybrid vehicle operation and that of the marine hybrid vehicle operation.

1. Diesel generators need to run continuously at a fixed speed and 50/60 Hz AC voltage, whereas hybrid vehicles are capable of operating at optimal loading points with speed change, gearshifts and mechanical decoupling between generator axle and driving axle [24].

2. Road based hybrid electric vehicles can benefit from regenerative braking energy, which can add to fuel savings. Whereas for marine applications, regenerative braking energy can be achieved in vessels with large cranes and drilling technologies that have heave compensation technologies [24].

3. The set rules and conditions in industry for BESS in the maritime sector can be very different from that of road based hybrid vehicles. In the case of marine vessels that have special operation such as the Dynamic Positioning (DP) mode, require the vessel to maintain its operation in the event of failure of any energy resource [24].

4. The load demand on marine vessels are heavily dependent on weather patterns, conditions, tonnage, depth at which the vessel is operating and geographic location. These parameters are never the same and can result in very different operational profiles. Road vehicles on the other hand, have regulated speeds that they may drive at in most parts of the world. This makes it easier understand the load profile and design a robust EMS controller [24].

5. The safety and technical regulations that have been set for marine vehicles are very different from that of road vehicles. Marine safety and technical regulations tend to be much more strict, given the possible consequences of a blackout in the sea. The safety and technical regulations for road vehicles can be a little less stringent, given hazard support on land being more accessible. Therefore, there can also be a limit to the different types of technologies, that marine vessels can employ for hybridization.

With these differences in mind, the hybrid vessel needs to aim for efficiency and operations optimization.

2.8.1. EMS roles on Hybrid Marine Vessels

Now that the difference between designing an EMS for hybrid road vehicles and vessels is understood, this section will delve into the roles of the EMS for marine vessels. The main objectives of the EMS on vessels include:

- Reduce fossil fuel consumption by diesel generators.
- Lower GHG emissions and noise pollution.
- Reduce generator maintenance costs, by optimizing the loading factor during operation.
- Aim for better energy efficiency with the application of RES and ESSs.
- Make sure the vessel meet redundancy and safety requirements.

Marine vessels face the problem of unpredictable load demands, as a significant percentage of their operations are offshore and are subject to oceanic conditions. The EMS needs to take into account the fluctuating load demands and effectively operate the DERs on the grid. By that process, it is possible to minimize fuel consumption, emissions and maintenance costs of the DGs. Additionally, the safety and reliability of the grid is ensured with the diverse energy sources onboard the vessel.

2.8.2. EMS tasks while managing BESS

1. **Fully Electric Operation** : During the various operational modes of the vessel, the battery serves as the sole energy source, thereby preventing the operation of one or more diesel generators at a low operating point.

2. **Spinning Reserve** : The main task of the BESS in this case is to provide energy support to the grid, in the event of failure of 1 or more generator components. The BESS supplies energy instantaneously for a certain period of time, which can vary depending upon customer and regulatory requirements.

3. **Start - Stop Mode** : If the vessel is operating at load demands that are at low loading points for the DGs, the EMS commands the batteries to meet the demand. The batteries continue to operate until it reaches the minimum SoC setpoint. Upon reaching that set-point, the DGs operate meeting the load demand and recharging the battery at the same time.

4. **Peak Shaving** : In the event of urgent load demand in the grid and the DGs are incapable of starting up immediately, the EMS instructs the batteries to meet the load demand up-to the point at which the DGs are online and take over.

5. **Load Levelling** : During events of load fluctuations, if the load demand exceeds the value of optimal loading of DGs, the BESS takes over and shaves off this excess demand.

6. **Charge Mode** : During the charge mode, the EMS is responsible to collaborate with the BMS, for ensuring that the charge power is well within the recommended C-rates provided by the manufacturer.

2.8.3. Different Energy Management Strategies for Hybrid Vessels in Literature

1. **Rule Based Algorithm** : The rule based algorithm is the simplest and computationally least demanding algorithm to meet minimization requirements. The minimization can be in terms of fuel consumption, carbon emissions or maintenance costs. The key features include simplicity of application and broad scope. This algorithm is heavily dependent on the knowledge of the programmer, the knowledge of different eventualities and quality of rule-sets placed to provide the most efficient fuel consumption solution.

2. **ECMS** : The Equivalent Consumption Minimization Strategy is an approach aimed at keeping fuel consumption to a minimum. The authors of [25], designed and developed an ECMS model for a tugboat's energy management system optimization. Their work achieved an estimated fuel savings of nearly 17.4%. However, one of the limitations of this method is that the minimization of fuel consumption also creates a possibility for an event wherein the grid cannot meet the load demands in a peak event. Additionally, the availability of shore power was an important factor that determined the potential fuel savings. The potential impact on battery health with deep cycling is not explicitly discussed.

3. **MPC** : The model predictive control strategy is employed to provide instructions to the various distributed energy resources on the grid, based on certain predictions the controller makes. The controller takes into account the current state of operation and makes predictions based on the available prediction solution space defined by the limitations of the powerplant. The authors of [26] demonstrated that via model predictive control, similar fuel savings can be achieved as that of the ECMS strategy. The key difference is that their control design could ensure the battery have sufficient capacity to assist in the peak demand operations, which was a limitation in the ECMS strategy as proposed by the authors of [25]. Additionally, the authors in this control strategy used simplified mathematical models to define the DER, due to computational complexities and the non-linear behavior of DER components.

4. **NSGA-II** : The Non-Dominated Sorting Genetic Algorithm II was developed by Kalyanmoy Deb [27]. The working consists of sorting two or more solutions on the basis of their ranks. Following which, the solution is ranked based upon it's crowding distance from the best solution [27]. The authors of [28] developed an EMS strategy for a hybrid ship consisting of DGs, PV panels, wind turbines and energy storage technologies. The application of the NSGA-II was aimed to reduce costs and GHG emissions. From their findings, costs were reduced between 13.17% and 17.53%. A key factor to be noted is that the inclusion of solar panels and wind turbines played an important role in cost reduction.

5. **PSO** : The Particle Swarm Optimization is an algorithm that comes under evolutionary computation. PSOs have the advantage of being relatively simple to formulate, quick solution convergence and efficient in locating the optimum solution. It also meets the requirements to flexibly calculate the optimum based upon the non-linear behavior of various components in the hybrid powergrid. The works of [29] developed an EMS for a hybrid roll-on - roll-off vessel, that consisted of DGs, energy storage technologies and photovoltaic panels for energy generation. Upon testing this designed EMS on the ship's operational profile, an estimated 23% reduction in fuel consumption could be established.

6. **Fuzzy Logic Control** : Fuzzy logic control technique is implemented to models with imperfect data and models. These control models are capable of working on models with vaguely defined control rules and logic, which is ideal for systems with non-linear behavior and characteristics. The authors of [30], developed a model in combination with dynamic programming for a hybrid powered vessel consisting of batteries, fuel cells, super capacitors and PV panels. The designed model is capable of operating the grid in extreme operating conditions and meet energy demands. It was found that hydrogen consumption in the fuel cells could be reduced by 14.39% and at the same time maintain the integrity of the battery. However, it is noted that these savings were achieved using the super-capacitors and the availability of solar irradiance over the course of this simulated study.

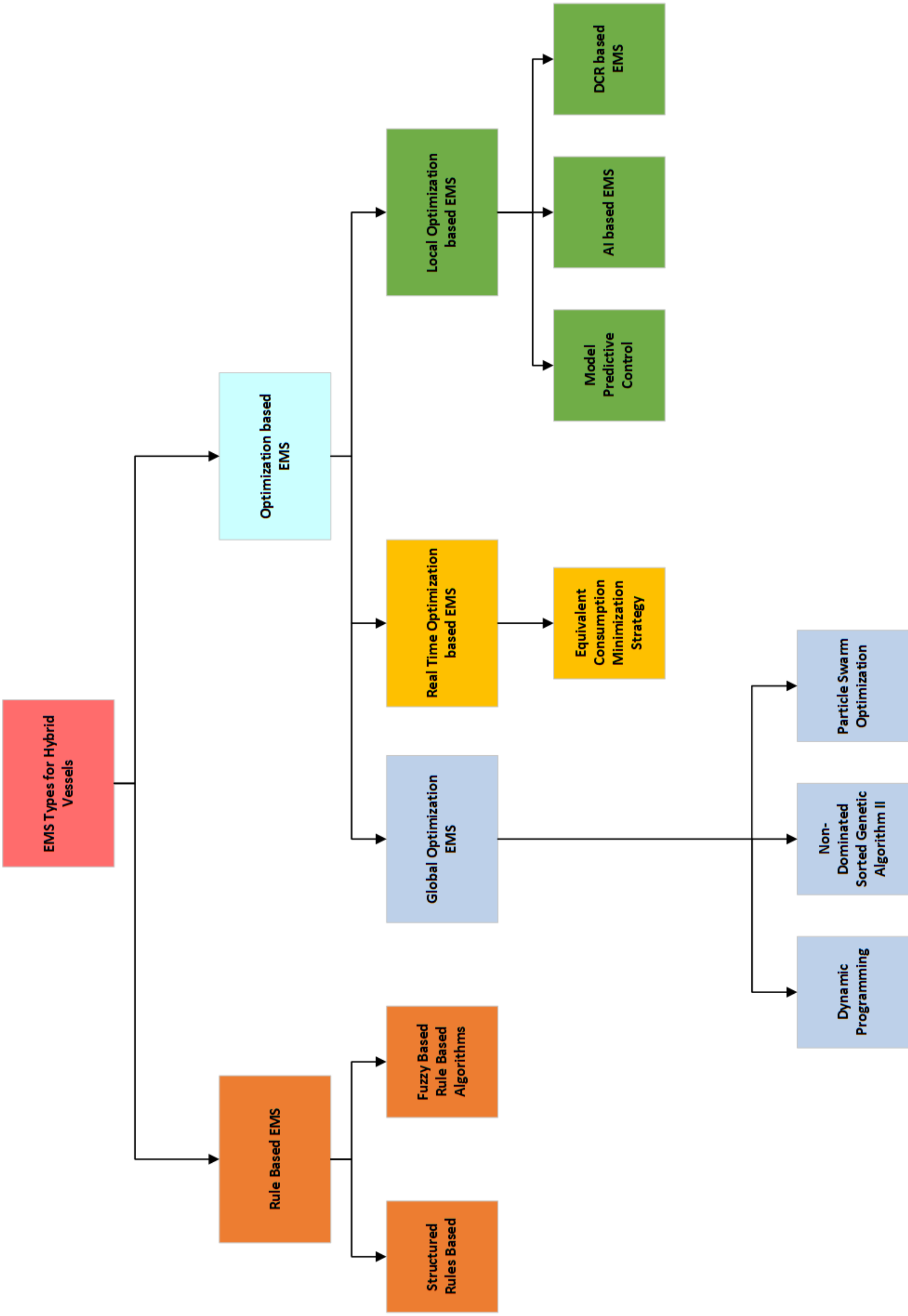


Figure 2.11: Overview of different EMS types for Hybrid Vessel application

3
Vessel Description

The objective of this chapter is to analyze the existing configuration of the vessel. The operational profile and data are analyzed to understand the problem at hand. Following this, some details into the proposed hybrid solution are investigated.

3.1. Configuration of the Vessel

The following figure 3.1, represents the single line diagram of the existing configuration of the cable laying vessel. In further descriptions, this network will be referred to as the electrical powerplant. The legend of this single line diagram is available on Table 3.1.

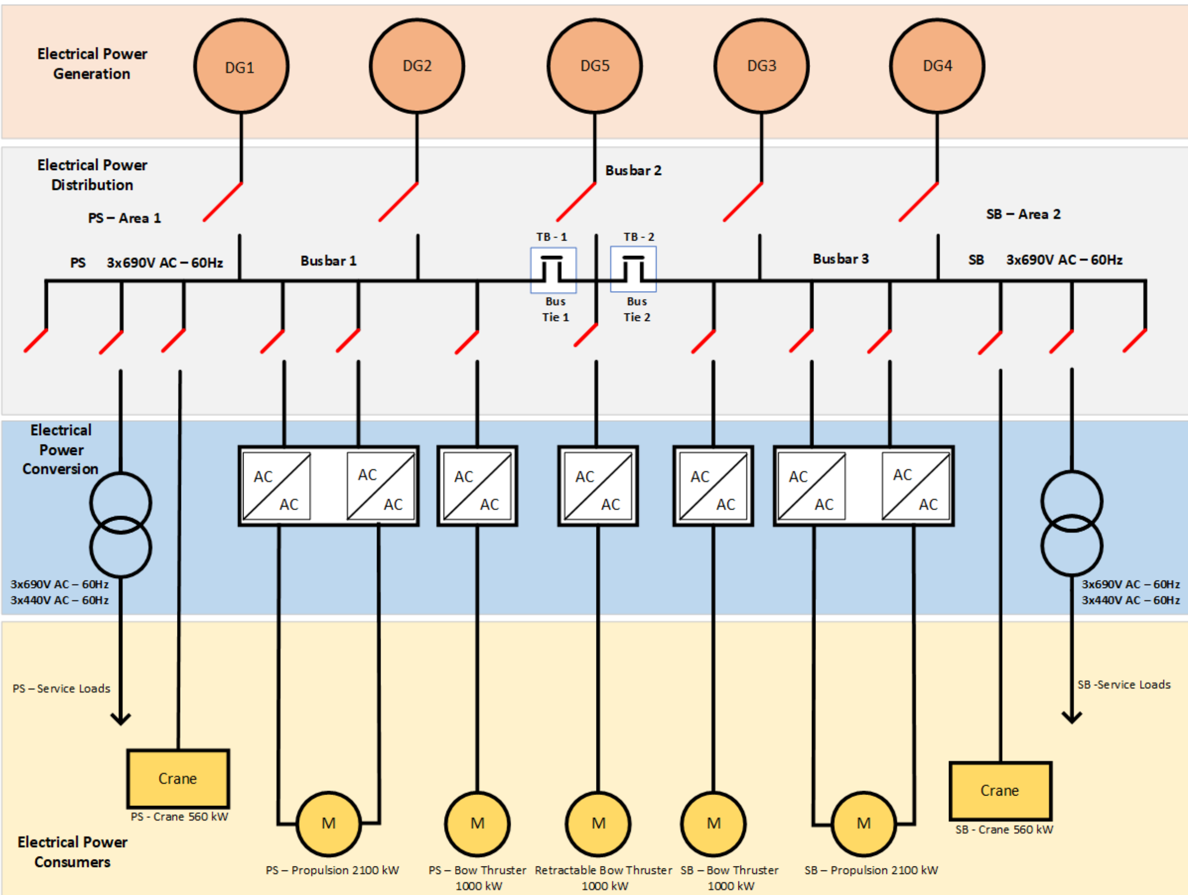


Figure 3.1: Electrical Single Line Diagram of the Cable Laying Vessel

The existing vessel consists 5 DGs, 2 cranes, 5 thrusters for propulsion and positioning, and service and hotel loads. For the purpose of electrical power conversion, the thrusters employ the use of variable frequency drives for speed control, whilst the hotel loads make use of a transformer. Table 3.2 details the rated power of the various generators currently installed and operated on the vessel.

Table 3.1: Legend of Single Line Diagram

Symbol	Legend
AC	Alternating Current
DG	Diesel Generator
PS	Port Side
SB	Starboard Side
M	Thruster Unit
TB	Tie Breaker

Table 3.2: Diesel Generator Power Rating

DG Number	Rating (kW)
Diesel Generator 1 (DG1)	1912
Diesel Generator 2 (DG2)	2560
Diesel Generator 3 (DG3)	2560
Diesel Generator 4 (DG4)	1912
Diesel Generator 5 (DG5)	1360

Furthermore, this vessel has predominantly 3 operating modes. This electrical powerplant consists of two bus tie breakers that provide electrical isolation between the Port Side and the Starboard side during the Dynamic Positioning Mode. A depiction of the various operational modes of this vessel is described by Table 3.3.

Table 3.3: Operational Modes of the Vessel

Case	Tie Breaker 1	Tie Breaker 2	Mode
Case 00	Open	Open	Dynamic Positioning
Case 01	Open	Closed	Non-Critical Dynamic Positioning
Case 10	Closed	Open	Non-Critical Dynamic Positioning
Case 11	Closed	Closed	Auto Mode

Table 3.4: Operational Tasks of the Vessel

Task	Possible Demand (kW)	Available Power (kW)	Mode
Harbor	851	1360	Case 11
Manoevering	5165	8392	Case 11
Free Sailing	5740	7032	Case 11
Loading/Unloading	6529	10304	Case 00
Dynamic Positioning	6971	10304	Case 00 | 10 | 01

It is noted that this vessel has the port side and starboard side electrically isolated during the operation cases 00,01 and 10. DG5 is the additional generator that is available for redundancy requirements and operation during the 01 and 10 operational cases. This vessel operates with 5 possible tasks, namely - Harbor, Manoevering, Free Sailing, Loading/Unloading and the DP mode. In line with the DNV GL class requirements, the available power and maximum power consumption during each mode is described by Table 3.4.

3.2. Request from Vessel Owner

The vessel owner approached Alewijnse to inquire about the possibility to hybridize the vessel in view of their sustainability ambitions. Key factors of interest include reducing Marine Gas Oil (MGO) consumption, emissions reduction and overall operational costs reduction. Thus, the decision of installing BESSs to the existing setup was made.

In order to design and size the BESS accurately, operational data was requested by Alewijnse. Upon analysis, it was determined that this vessel operates a significant percentage of it's operations in the DP2 mode. For more details into DP2 mode, please refer Table 2.1. Two load data profiles were provided by the vessel operator, during their operations in the Taiwan Strait and North Sea. The configuration of the vessel in this mode and bus tie states can be viewed in Table 3.3

3.3. Analysis of Operational Profile of the Vessel in DP2 mode

In order to effectively design a hybrid configuration for this vessel, it is necessary to analyze the load profile to make informed decisions. Based on the data shared by the vessel operator, this vessel has operated predominantly in two regions of the world. The first dataset was recorded in the Taiwan Strait. The second dataset was recorded in the North Sea.

3.3.1. Taiwan Strait Load Profile Analysis

An analysis into the load data from this Vessel in the Taiwan Strait, indicate the following insights. **The following data was logged every 5 minutes by the Vessel Operator**. A total of 38,727 loading events were recorded in this space, which comes to about 134.5 days of continuous operation time. From figure 3.2, the load demand experienced on the Port Side is presented. It is observed that in the DP2 mode, the vessel load demand is significantly lower than the rated capacities of the DGs available on the grid. Majority of the loading events experienced by the vessel is found to be less than 800kW, which comes to 42% of the rated capacity of DG1, which is rated at 1.912 MW. The number of loading events valued between 800 kW and 1912 kW, is observed to be just above 1000, whilst load demands greater than 1.912 MW have all been recorded below 10. A closer look at figure 3.3, indicates that the in the Taiwan Strait that majority of the loads lie between 300 kW and 800 kW. The attribute can be related to the fact that the seas in Taiwan Strait region are quite calm, with very rare instances of wild seas. From figure 3.4 and figure 3.5, it can be noted that for a significant portion of operation, both the diesel generators have been operated well below 30% of their rated capacities.

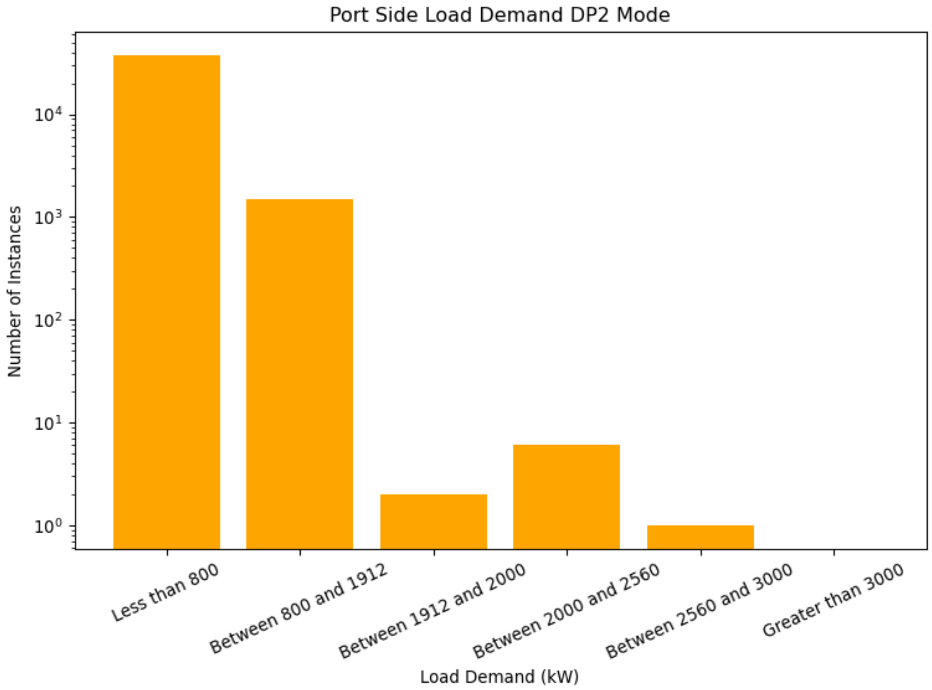


Figure 3.2: Load Demand Overview in DP2 mode in the Taiwan Strait on Port Side

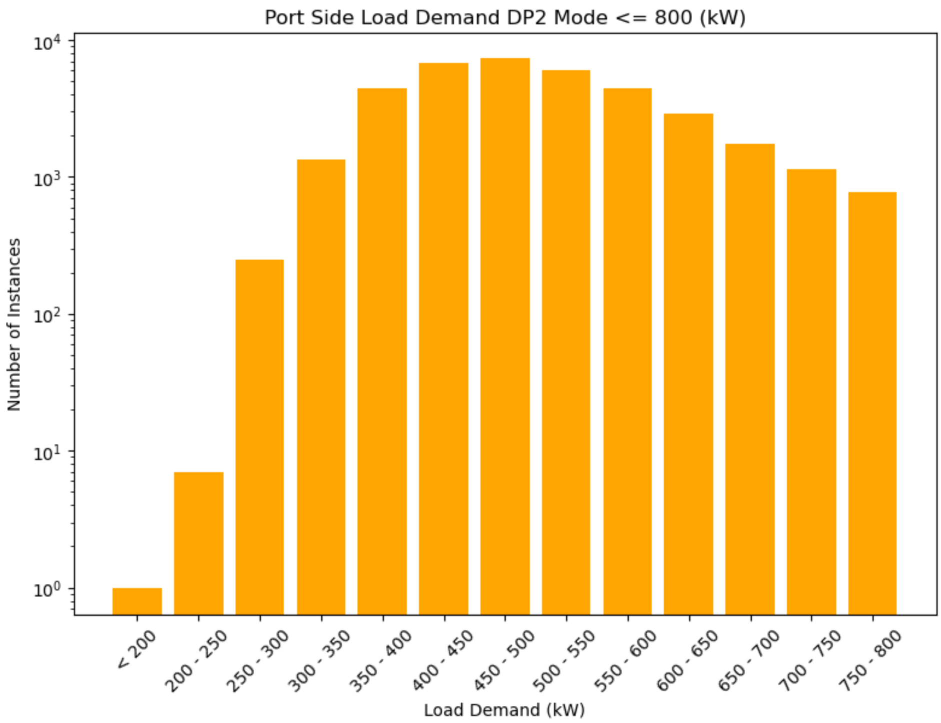


Figure 3.3: Load Demand Instances less than 800kW

From table 3.5, it is noted that this vessel has operated the DGs at a non-optimal load [31], most of the time. The non-optimal load range between 0% and 30% was run by all the DGs in the DP2 mode for an average of 119.5 days of continuous operation time.

Table 3.5: Diesel Generator Loading Data in the Taiwan Strait

DG Number	Loading Range	Duration (Days)
DG1	0 - 30 %	117.5
DG2	0 - 30 %	121.3
DG3	0 - 30 %	121.1
DG4	0 - 30 %	118.2

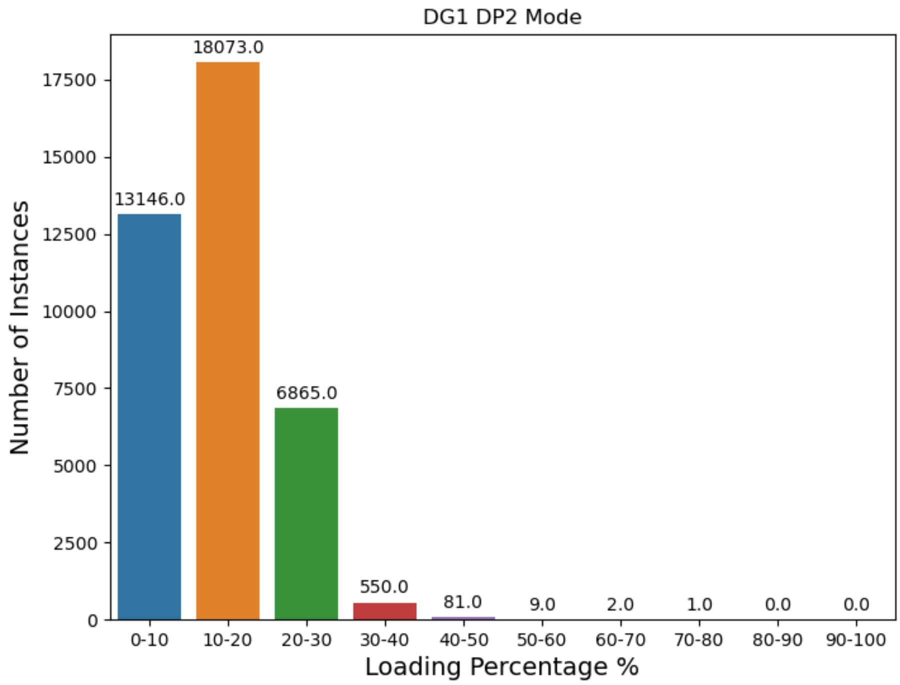


Figure 3.4: DG1 Loading in the Taiwan Strait

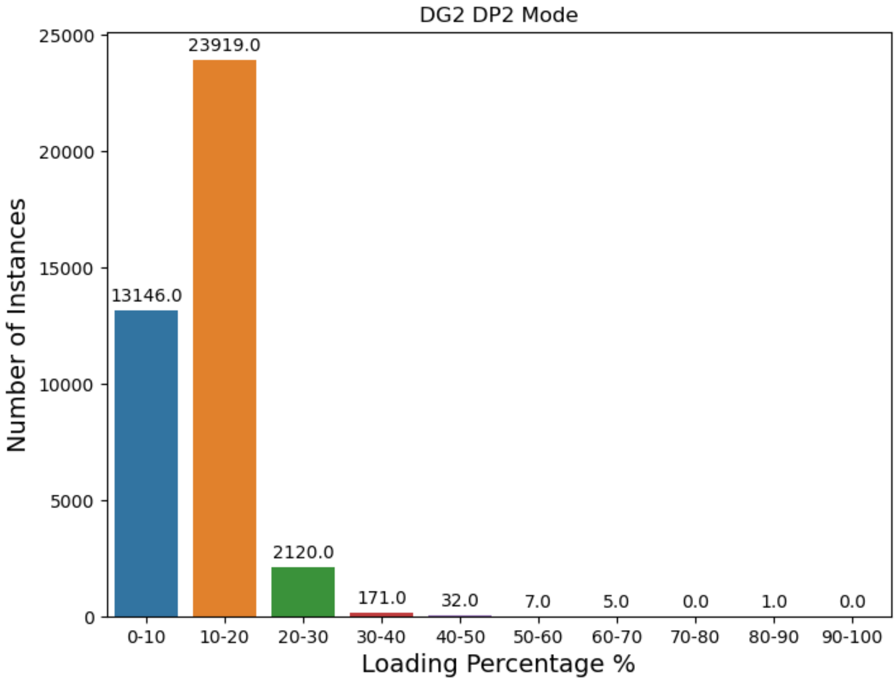


Figure 3.5: DG2 Loading in the Taiwan Strait

3.3.2. North Sea Load Profile Analysis

Upon analysis of the North Sea data, it is noted that the loading events up-to the rated capacity of the second DG has been reached over 10,000 times. **It is to be noted that the data logged by the vessel operator, in this region was in 1 minute time intervals**. However, similar to the Taiwan Strait, the DGs are mostly under utilized. Figure 3.6 indicates 100,000 instances, when the load demand was less than 800kW. There are over 40,000 instances, when the load demand was between 800 kW and 1912 kW. At the same time, in the North Sea, there is a load requested of up to 3000 kW. This can be attributed to the fact the North Sea has more chaotic waters, prompting the DP2 control mechanism to demand more power. The DP2 control keeps the vessel in its desired location coordinates. From figure 3.7, it can be seen that there were several such instances wherein the net load demand was lower than 200kW, with a significant percentage between the range of 250 kW and 800 kW. From figure 3.8 and figure 3.9, it is noted that DG1 operates most of the time in the loading range of approximately 20% and 30%. Whereas DG2 operates most of the time in the loading range of approximately 10% and 30%. At the same time, DG1 and DG2 have operated at load demands greater than 80% for 7.47 days and 7.39 days respectively.

Table 3.6: Diesel Generator Loading Data in the North Sea

DG Number	Loading Range	Duration (Days)
DG1	0 - 30 %	75.6
DG2	0 - 30 %	69.9
DG3	0 - 30 %	69.7
DG4	0 - 30 %	76

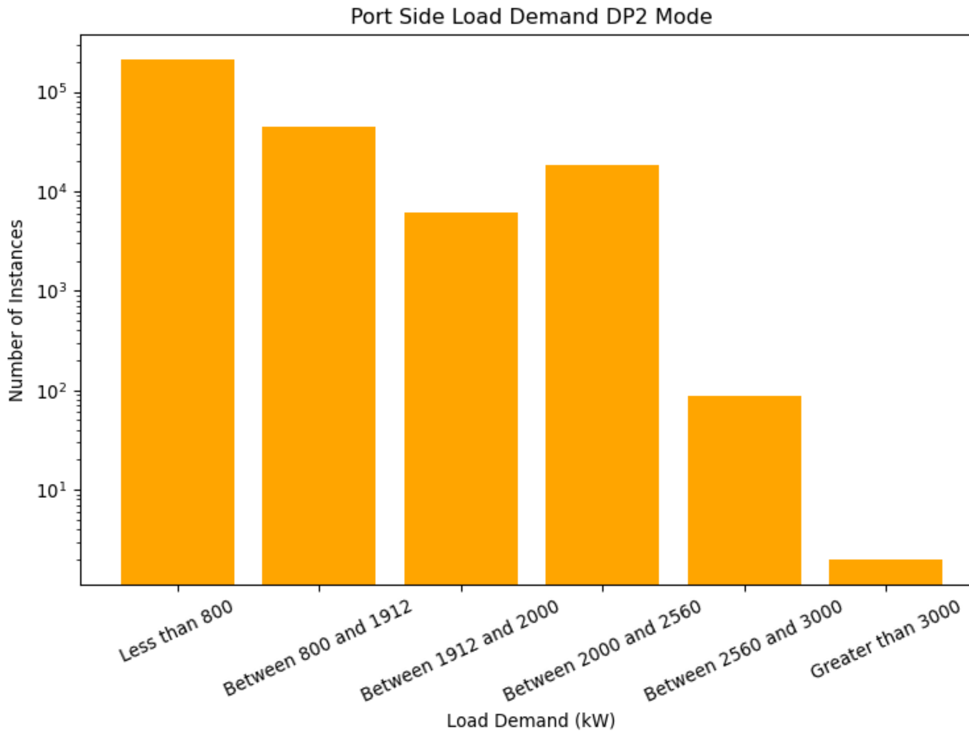


Figure 3.6: Load Demand Overview in DP2 mode in the North Sea on Port Side

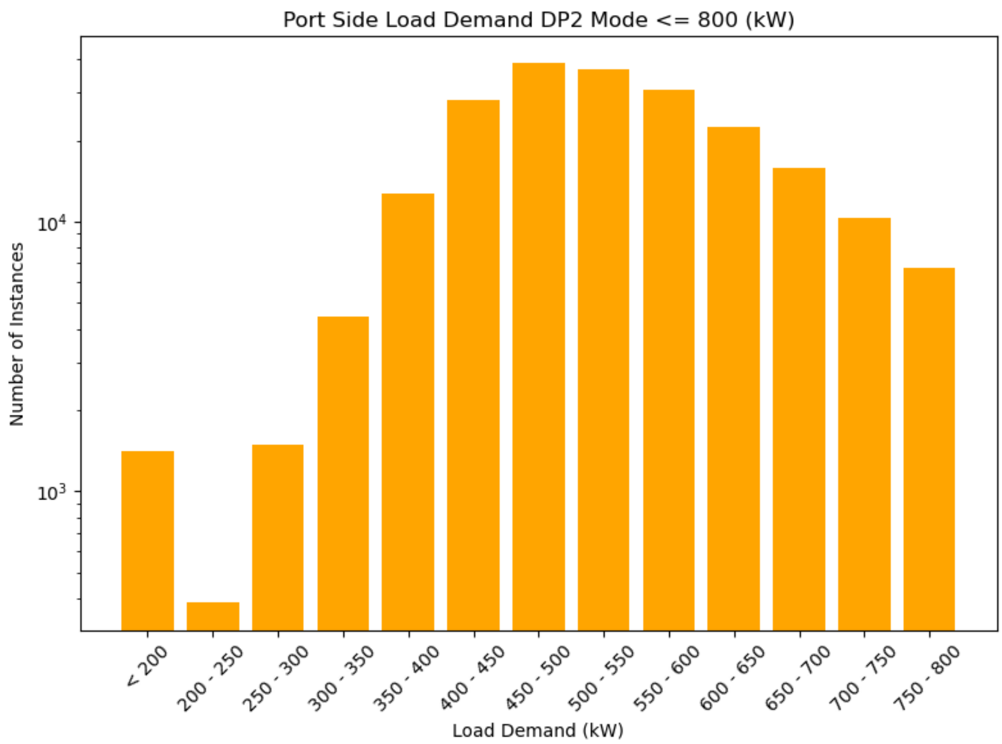


Figure 3.7: Load Demand Instances less than 800kW

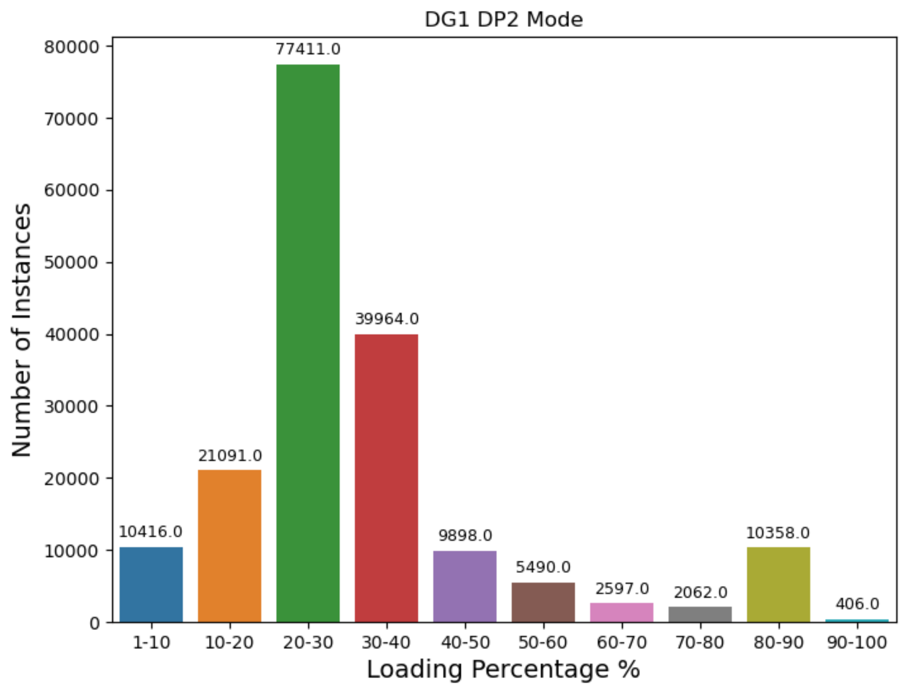


Figure 3.8: DG1 Loading in the North Sea

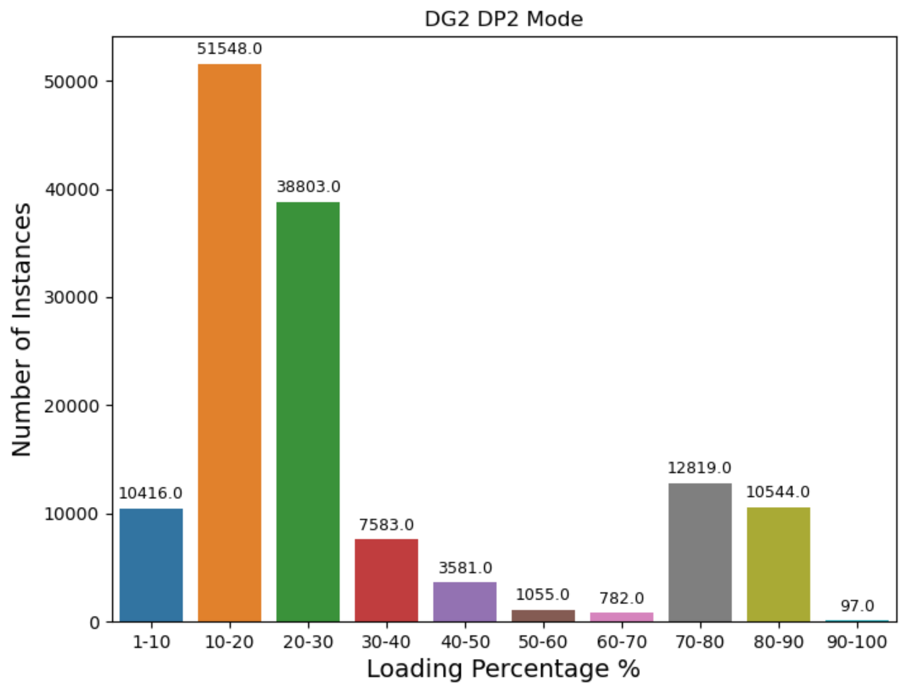


Figure 3.9: DG2 Loading in the North Sea

3.4. Findings from Vessel Operation Data

Upon analyzing the specific fuel oil consumption curve against the loading percentage of a specific generator, it can be inferred that higher loading of the generator results in lower specific fuel oil consumption (SFOC). The current average SFOC for DG1 varies between 0.4793 L/kWh and 0.2611 L/kWh. Parallely, DG2's average SFOC varies between 0.4367 L/kWh and 0.2602 L/kWh. When analyzing the MTBO curve and SFOC curve in combination, it can be noted the ideal loading points for the these generators can be between 55% to 80%. By this metric, there is the opportunity to make the most of the overhaul cost savings and at the same time, minimize fuel consumption. Loading the DG below 55% increases the probability of wet-stacking and damage to engine components. The SFOC below 55% DG loading is also relatively high as indicated by the figures 3.10 and 3.11.

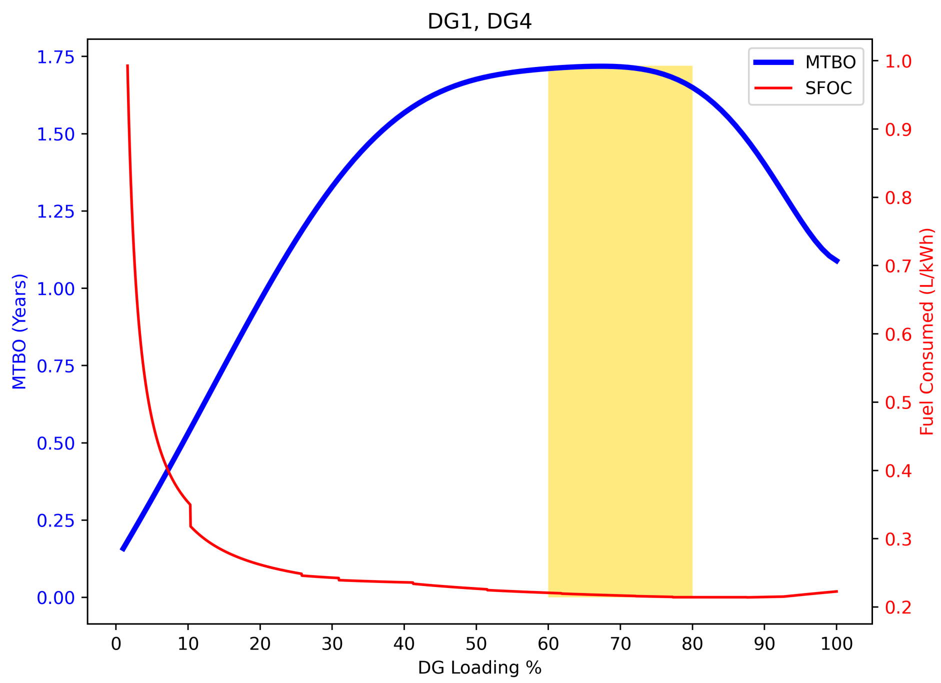


Figure 3.10: DG1,DG4 MTBO and SFOC Curve

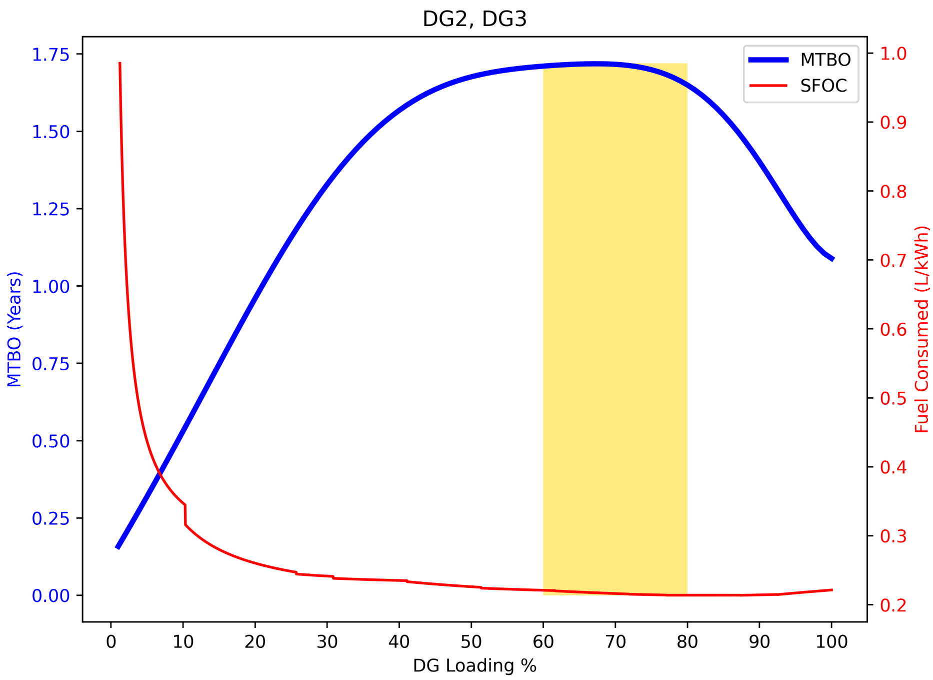


Figure 3.11: DG2,DG3 MTBO and SFOC Curve

The SFOC continues to decrease as the DG loading % increases. From the data provided by the operator, it is evident that the SFOC in minimum at 88% loading. However, the MTBO Curve also indicates that loading the DG above 80% of it's rated capacity, increases the probability of wear and corrosion of the DG components, thereby reducing the MTBO timeframe. From the operational analysis of the Vessel, it is clear that the EMS needs to focus on controlling the DER on the grid, with focus on the SFOC, MTBO and the continuously varying load profile during the DP2 operation mode. Therefore, the focus on the EMS controller should be to load the DGs in the range of 55% - 80% of their rated capacities. Thus, in view of these criterion and data applied to this specific vessel, a hybrid solution can be applied to meet operational requirements.

3.5. Proposed Hybrid Configuration of the Vessel

From the data above, it is evident that the vessel needs to be optimized in order to improve it's fuel consumption efficiency and reduce maintenance expenditures. With the IMO guidelines in mind and desire to green the vessel, the proposal to make use of BESS has been made. Class requirements set by the Det Norske Veritas Germanischer Lloyds (DNV GL) was also considered, when deciding the technology for energy storage. Based upon research and development conducted at Alewijnse, two 1MWh rated BESSs was decided. The Single Line Diagram of the proposed hybrid vessel can be seen on figure 3.12. The expected tasks of the BESS are listed in section 3.5.1.

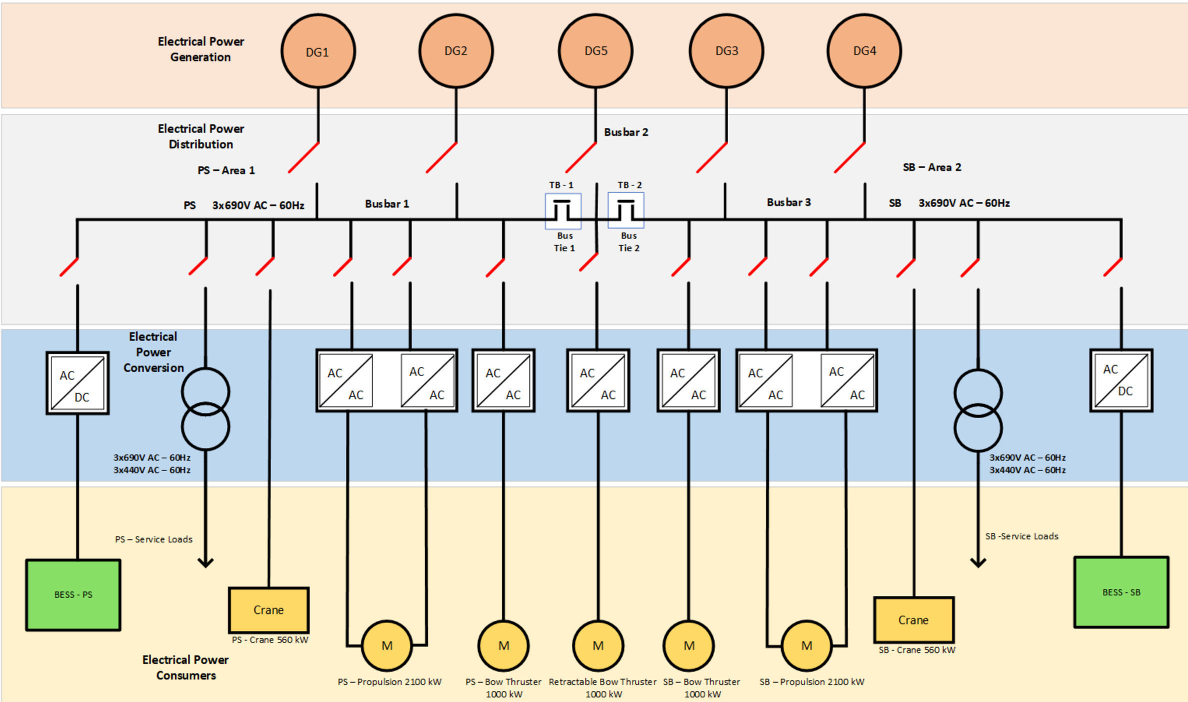


Figure 3.12: Electrical Single Line Diagram of the Proposed Hybrid Cable Laying Vessel

3.5.1. Main Roles of BESS for this Vessel

From the information above, the BESS predominantly has the following specific roles.

- **Spinning Reserve** : The BESS supports the network in the event of failure of generator components. It acts as the sole energy provider for the vessel until the generators are able to connect back to the grid.

- **Start - Stop Mode** : In the event wherein the loads are consistently low over a long period of time, the BESS continues to meet these load demands until it reaches the preset minimum SoC. Upon reaching this level, the DGs start up to meet the load demand and charge the battery. By this approach, it is possible to maintain the DG to operate at an optimal loading point.

- **All Electric Mode** : The primary objective of this mode is to reduce the carbon emissions and noise created by the DGs at a non-optimal loading point. The BESS meets energy requirements in these instances to reduce DG operation at low loads.

- **Peak Shaving** : In the event the the load demand exceeds the capacity of the main operating DG, the BESS shaves off this additional load, thereby preventing the operation of another DG at a non-optimal point.

- **Load Levelling** : In this operation, any excess load demand, that is outside the optimal loading range of a DG, is met by the BESS. This demand is met by the BESS as long as the the demand lies in a region of non-optimal operation for the next DG. Therefore, this operation prevents the use of a DG in a non-optimal load scenario, reduces fuel consumption, GHG emissions and wet-stacking events.

This chapter discussed the specific details of the vessel under study. The load profile, the configurations and expectations from the BESS. The following chapter 4 discusses the use of Typhoon HIL for this study.

4
Modelling On Typhoon HIL

The objective of this chapter is to understand the modelling process of this vessel in the Typhoon Hardware in Loop system. This chapter also discusses limitations and challenges that were associated with this software. Additionally, the SCADA panel developed and user interaction process is described. For information regarding the specific details of the vessel, please refer to chapter 3.

4.1. About Typhoon Hardware in Loop Solutions

Typhoon Hardware in Loop (HIL) is a software emulation platform developed by engineers and scientists for engineering applications. The company is based in the Republic of Serbia and the US. The ”HIL” device developed by Typhoon GmbH is a one stop solution, for real-time digital simulations of developed designs for power electronics, drive systems, control systems and more. In the HIL test platform, the HIL machine is referred to as the ’hardware component’ in the test. The HIL device is connected to the micro-controller, which is now connected to the simulation environment of Typhoon HIL. The micro-controller now forwards signals to the HIL device in a similar manner as in the real world scenario. In return, the HIL device processes these signals, computes complex mathematical problems and returns an output signal as required by the micro-controller. The key benefit of this approach is that since the results are achieved in real time, it helps developers and engineers validate the authenticity, performance, safety and reliability of their product at a minimal cost. Additionally, there is no need for lucrative investments into physical prototype development and there are no safety hazards for human life and equipment.

The Typhoon HIL device and software are designed for the purpose of achieving high-fidelity results in the real time sphere. C-HIL is a development and testing platform, wherein an actual physical controller is connected to the high-fidelity plant model simulated in real time. In this process, the controller operates as if it were working in real world scenario and carries out its various tasks and operations. By this method, engineers and scientists can validate the feasibility of their designs, conduct several different test scenarios including scenarios that include risk of damage to understand the limits of the model.

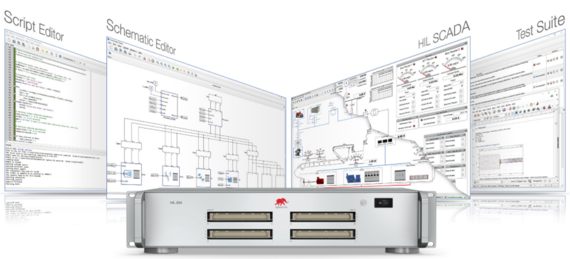


Figure 4.1: Typhoon HIL Platform [32]

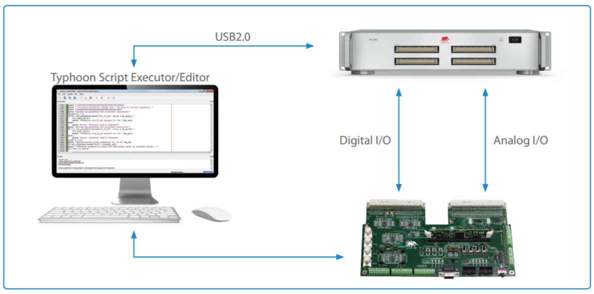


Figure 4.2: Controller and HIL Device [32]

4.2. HIL Device Architecture

This section provides a brief overview into the Hardware-in-Loop device. The architecture, and CPU types and roles are discussed.

- **FPGA Solver** : The FPGA solver developed by Typhoon is an FPGA-multi-core processor that is optimized for real time simulation of **electrical domain models**.
- **System CPU** : There can be one or more of these general purpose processors that are controlled by the user indirectly. The main purpose is to aid the FPGA solver with certain low dynamics electrical domain components.
- **User CPU** : This processor is usually under direct control of the user. They are mostly used to execute and simulate low domain electrical signals and controls.

Figure 4.3: The Typhoon HIL FPGA Solver [32]

4.3. Motivation to Use Typhoon HIL

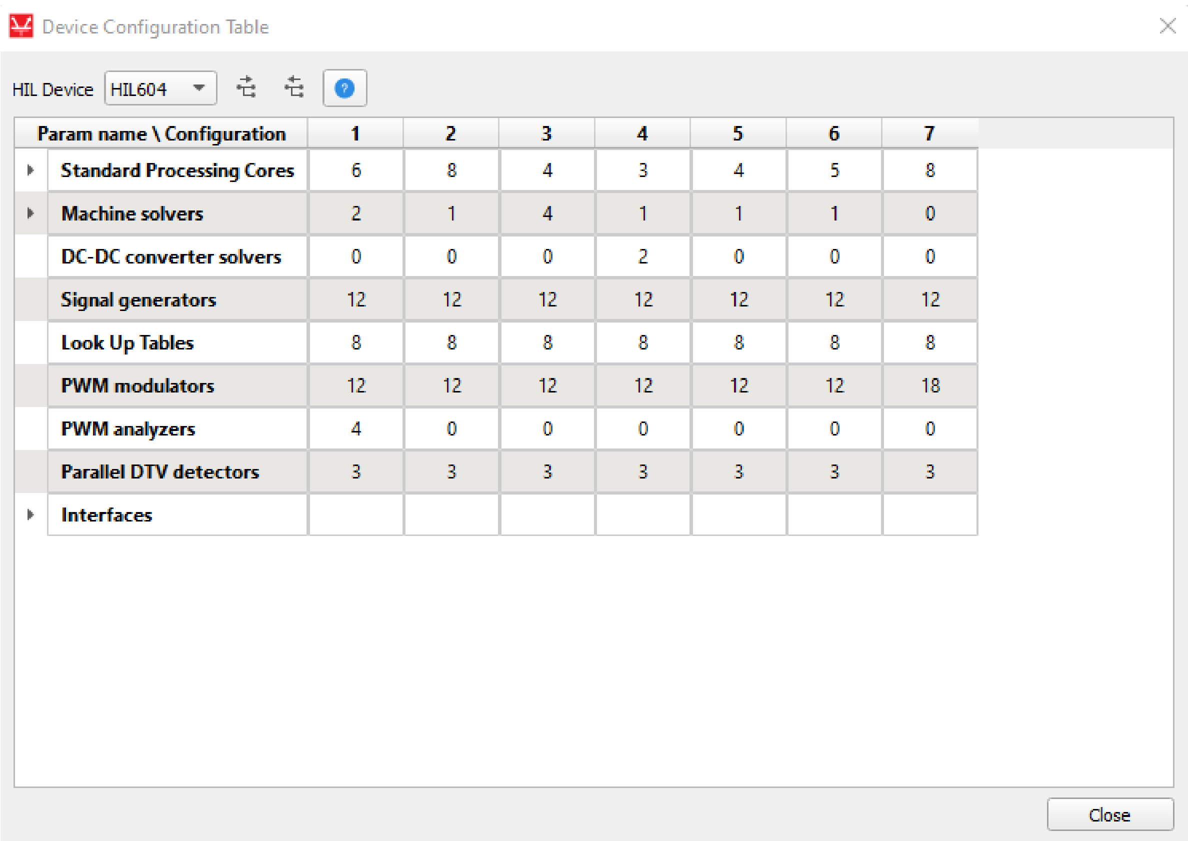
In order to validate the proposed model of the Hybrid Vessel, it is necessary to model and simulate results that are of high quality and reliability to make an informed engineering and investment decision. Some of these decisions can include possible changes to the existing proposal such as the battery sizing, use of power electronic converters, EMS control strategy and investment into configurations that can have the best return on investment for the client. Therefore, the development of a state of the art Digital Twin, mimicking the hybrid vessel, with a SCADA platform for testing, is preferred. The reasons for selecting Typhoon HIL for this project are stipulated below:

- Typhoon HIL tools and packages consist of the software and hardware currently available in most computer systems. There is no requirement for third party products, thereby ensuring a seamless user experience.
- Typhoon HIL's schematic editor and SCADA development platform consist several libraries with a variety of components that are available for several different applications and projects. These components are designed to emulate real world components, thereby providing high quality results.
- With the click of a few buttons on the SCADA dashboard, it is possible to analyze and simulate different operations of different configurations in the digital platform.
- Testing costs can be significantly reduced with the HIL test platforms, thereby ensuring safety of personnel and equipment.
- The HIL Automation platform makes it possible to test and develop testbeds that can run for a long duration and reduces repeatable tasks for the human developer.
- Design and development can be conducted quickly on a variety of test scenarios. Thereby, it enables faster entry of the product into the market and ensures competitiveness of the firm.

4.4. Model Development on Typhoon Hardware in Loop Platform

The Typhoon Hardware in Loop Company was contacted in the months of September - October 2023 regarding Alewijnse's requirements for the software emulation of the proposed hybrid vessel. In collaboration with TU Delft, the HIL device 604 was procured for this research project. The HIL 604 is among the most powerful HIL devices that Typhoon HIL has to offer. It is used for real time power electronics simulations, product development, testing, optimization and reliability assurance for a variety of industries. Several different industries currently employ this HIL device, which includes maritime, automotive, micro-grids and industrial automation [32].

Each FPGA solver consists of a certain number of standard processing cores (SPCs). The SPC is the basic building block of the circuit solver. It is responsible for the simulation of electrical circuits that have linear passive elements, converter blocks that have ideal switches and contactors that have ideal and non-ideal switches. The SPCs are connected to each other using specific communication lines, which enables it to update variables in a single simulation time step delay, in the range of microseconds (μs) [33]. The machine solver simulates and emulates an electrical machine including its electromagnetics, mechanics and speed measurements based upon the solver configuration. Similarly, the PWM modulator for power electronic components can be used both internally to drive converter components and externally through digital inputs. The capabilities of a single device for this modulator can be found on the solver configuration as specified by the documentation [33]. The device configuration table for the HIL 604 machine is presented by figure 4.4.



Param name \ Configuration	1	2	3	4	5	6	7
Standard Processing Cores	6	8	4	3	4	5	8
Machine solvers	2	1	4	1	1	1	0
DC-DC converter solvers	0	0	0	2	0	0	0
Signal generators	12	12	12	12	12	12	12
Look Up Tables	8	8	8	8	8	8	8
PWM modulators	12	12	12	12	12	12	18
PWM analyzers	4	0	0	0	0	0	0
Parallel DTV detectors	3	3	3	3	3	3	3
Interfaces							

Figure 4.4: HIL 604 Device Table with Computational Availability

4.5. Limitations of the 604 HIL device

Based upon the single line diagram of the existing vessel and the proposed vessel, the engineering team at Typhoon HIL determined the following changes to the modelling of the vessel using the 604 machine. Due to the size of the vessel and various power electronic components and electrical machines, the computational demand on one single FPGA solver of the 604 type would be immensely demanding. An overview of the different components and SPCs available for the 604 machine, in different device configurations is presented by Figure 4.4. Therefore, with computational limitations in mind, the hybrid model proposed by Typhoon HIL for this study is presented below in figure 4.5.

As seen on figure 4.5, there is the requirement to exempt the use of the variable frequency drives (VFD) that are used to control the thrusters. Given that the VFDs are complex power electronic components that control the speed of the thrusters, simulating and computing their operation in real time, is challenging for one HIL machine alone. Additionally, given that the focus of this study was on the integration of BESS, the bidirectional converter used is of the switching type, thereby mimicking real time dynamics. There was also the proposal to exempt the use of DG5, whose rating can be found in table 3.2. Given that this vessel operates a significant portion of it's time, with it's bus ties open, this additional recommendation was adhered to.

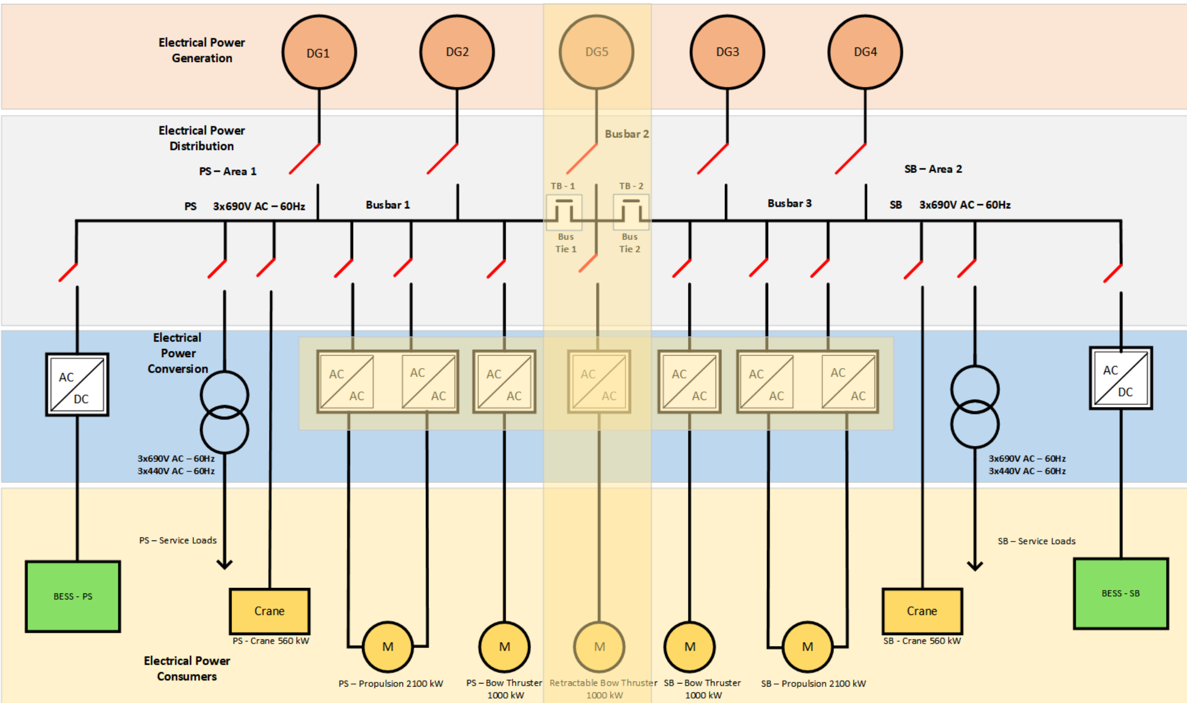


Figure 4.5: Hybrid Vessel Configuration suited to meet HIL 604 Computation Requirements. The region covered by the yellow blocks represent omitted components.

Finally, the choice of components for model development are as follows. The Typhoon HIL engineers determined the best configuration consists of the use of generic components for the diesel generators, average components for the thrusters and switching components for the bidirectional battery power converters. The purpose of the generic component is to directly make use of the simplicity it offers with the application of the component's nominal values. This feature eliminates the need for detailed filters and control data of the generator component. Ideally for the use of system integration applications and EMS control design, generic components for the generators can be useful. The average components are used in the case of the thrusters, given the absence of VFDs, the average model of the thruster was designed by Typhoon HIL to obtain realistic simulation dynamics of a PWM converter. Finally, in the case of the bidirectional power converter for the BESS, switching components are employed to obtain the maximum realistic solution possible. Switching components are employed when detailed power electronic component models for simulation are desired.

Following the recommendations of the Typhoon HIL team, the model of the hybrid vessel was designed as shown by figure 4.6. Whilst modelling the system was a relatively straightforward process, the key challenge to this step was to achieve model stability. Core couplings as labeled in figure 4.7, are components used to divide the entire circuit to smaller circuits that can be simulated in different cores of the HIL machine. Each HIL machine has a certain number of SPCs, which have a certain limit to machine solvers and PWM solvers. The ability of the HIL 604 machine and it's different configurations is explained by figure 4.4. The positioning and tuning of the core coupling component is of extreme importance so as to get results in real time [34], [35]. In the event the coupling is placed in a non-ideal position or tuned incorrectly, it can result in topological conflicts, arithmetic overflow errors and model instabilities. The values that determine the tuning of the core coupling components are achieved via trial and error as there is no clear mathematical model or diagram that can be referenced. Model stability problems can include illogical values such as the grid voltage being of the measure of a few million volts, the machine speed of the thruster having a negative speed of around -5000 rpm or the grid frequency unable to stabilize once the load demand changes.

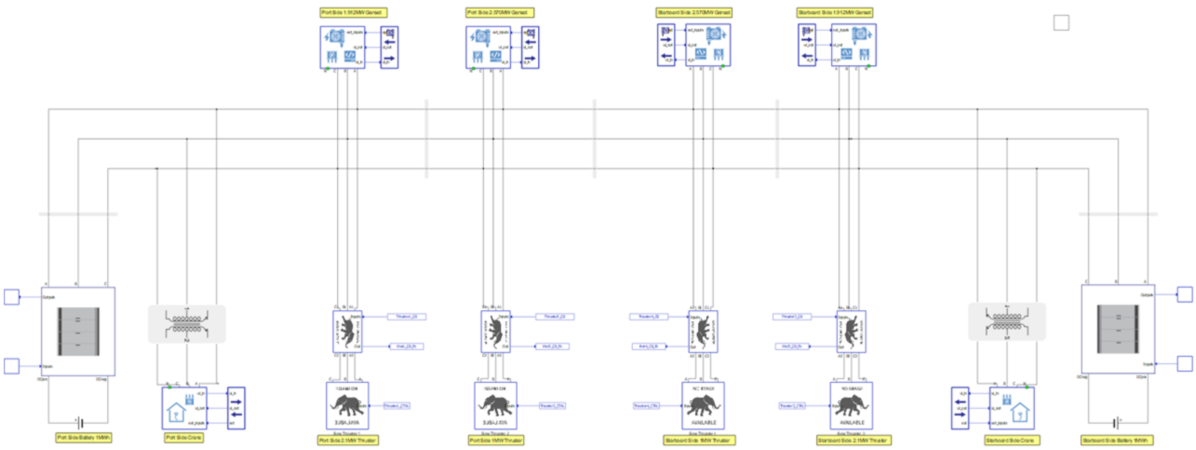


Figure 4.6: Original Model Designed

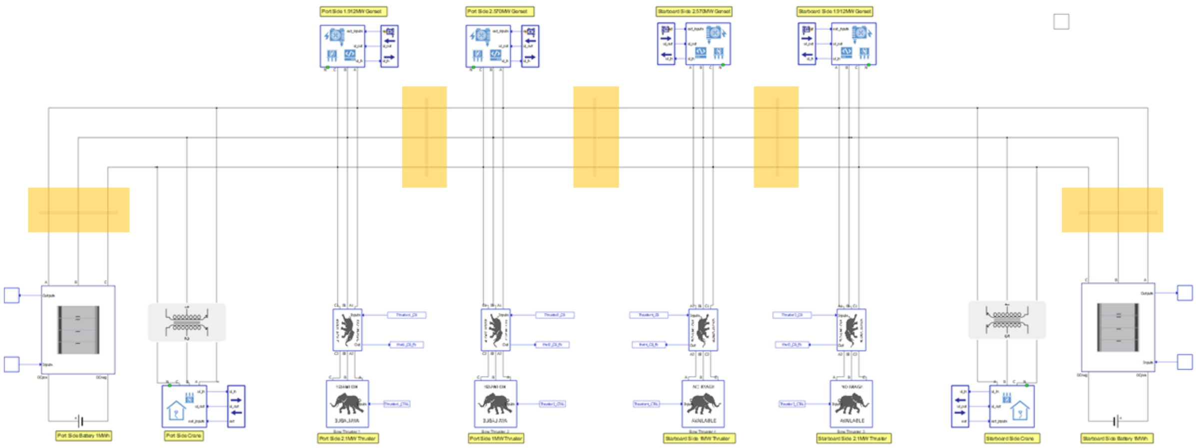


Figure 4.7: Core Coupling in designed model

Additionally, the inductive components for tuning the cores can create some voltage imbalance on the grid and will need to be stabilized using reactive power from the DERs in the grid. There was also the observation that the model and core coupling component's parameters were stable for the virtual HIL mode, but not for the real time mode. One drawback of the virtual HIL mode is that the simulation can take several hours to simulate 1 actual hour of the circuit, given the various components and simulation timestep of the range of 2 microseconds. Despite having lengthy discussions with the Typhoon Support team, it was not possible to achieve a stable model for the entire vessel. It remains unclear if the root cause of the issue is improper tuning of the core couplings, positioning of core couplings or if there was some other limitation of the HIL device that was being used in this study. Finally, in view of making the most of the available resources, it was possible to model the complete port side without any further model stability issues. In view of this vessel operating a significant percentage of time in the DP2 mode, it was decided to focus this study on the DP2 mode EMS control using the BESS. The developed model is further described in chapter 5. Figure 4.8 consists of the complete island grid that operates in the DP2 mode, along-with the proposed EMS Controller that efficiently manages the DERs in the grid.

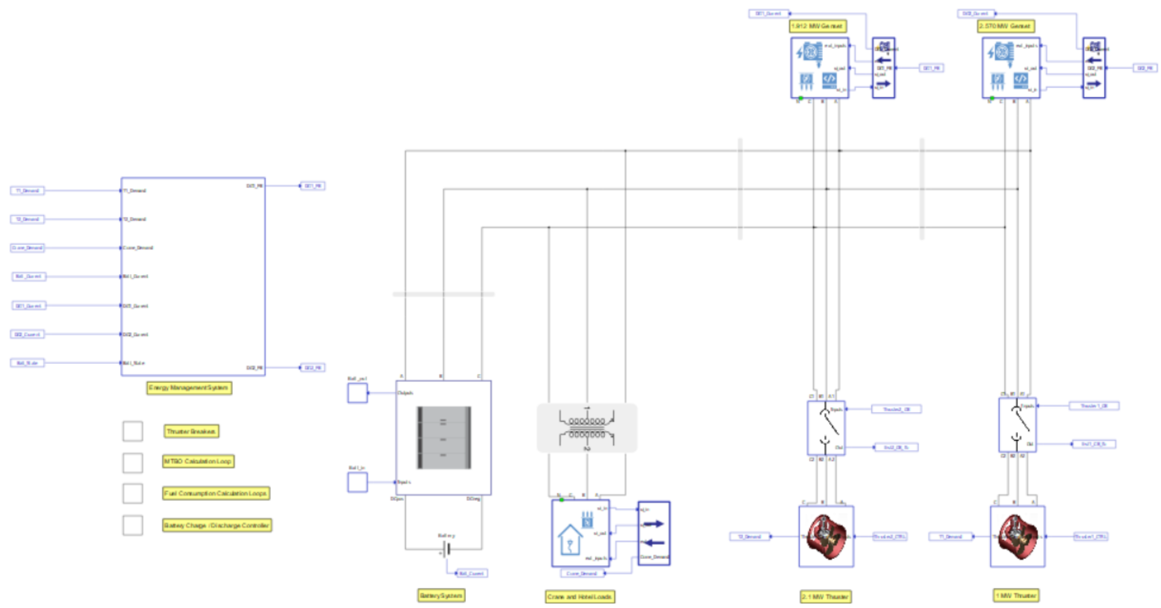


Figure 4.8: Final Model that was developed

Furthermore, it was noted from the available data, that this vessel operates a most of it's time in the DP2 mode. In the DP2 mode, the bus ties are open, please refer Table 3.3 for more details. In this mode, the vessel operates two separate island grids, as shown by figure 4.8. Hence, this model could provide valuable insights into this vessel's operations in the hybrid configuration.

4.6. SCADA Dashboard

The SCADA dashboard is where the real time simulation results can be monitored and downloaded. There is also the added feature, wherein the control engineer can interact with the dashboard. Changes to different components can be made, to understand the response and operation of their designs. Based on this ability, the robustness of the controller for the actual vessel can be tested exhaustively. The dashboard attempts to give an overview of the vessel operator's view on the bridge. And by far, operate the digital twin as if they were the vessel operator. In some design cases, the control engineer can change the load outputs from each generator or BESS component to meet a certain load demand. In this thesis, the EMS is automating the process of meeting load demands, with the most efficient energy provider available at the time. Therefore, on the SCADA dashboard of this model, user controlled changes are limited to the load demands. They are the thrusters, the crane and hotel loads respectively.

The designed EMS controller is to be implemented in the Typhoon HIL system. Alongside the challenges faced with ensuring model stability, it was also noted that with the existing HIL machine that was available, it was going to be problematic to implement global optimization packages. The packages that can be implemented in the Typhoon HIL device to the best knowledge of the author is through python. However, the way the HIL system is built, is such that the SCADA interface runs on Python scripts. Therefore, if any python based machine learning or scipy or other optimization packages is to be implemented, it needs to be done in the SCADA interface.

At the same time, the SCADA interface uses the python API for management of the various widgets, that are part of the SCADA dashboard for monitoring and data acquisition. Each widget on the SCADA dashboard represents the measurement of a certain value of a certain component, on the grid that needs to be monitored. Figures 4.9 and 4.10 provide an overview of what the SCADA panel looks like on the Typhoon HIL platform for this vessel. Each widget that logs a certain important datapoint needs to be continuously updated in 250ms, 500ms or 1000ms. The selection of the update interval would depend upon the number of widgets the the entire panel consists of and the number of HIL machines connected in parallel to compute. The control of these widgets run on python and with several widgets that need to updated instantly, with the time intervals explained above, the computational demand on the HIL device can be quite high. The Timeslot Overrun Error (TSO) is raised whenever the HIL SCADA computation time exceeds the provided timeslot [36]. This happens because the HIL SCADA cannot make all these calculations within the set timeslot, due to the detailed embedded scripts in the model, macros, and the number of widgets [36]. A solution to overcome this problem is to reduce the complexity of the embedded python scripts, and to delete any unnecessary widgets if the number of HIL devices are limited [36].

Therefore, with these limitations in place, it was decided to operate the model without the use of specialized python packages for global and local optimization problems. The model was simplified, with the use of Control Loops and the C function modelled on the Schematic Editor. The optimized EMS controller designed for this vessel, is shown in figure 4.11. The control approach used is the Rule Based Algorithm. The Rule Based algorithm is relatively simple to implement and is perceived to be one of the earliest methods of control for hybrid vehicles [37]. The implementation of this algorithm is dependent on the knowledge of the developer, intuition and mathematical formulae. It does not require knowledge of future events for implementation [37], [38]. The controller for this system takes in current data about load demand from the various consumers, the existing output from DG1, DG2 and the BESS to make the ideal decision, to operate the DERs efficiently to maximize savings and minimize fuel consumption.

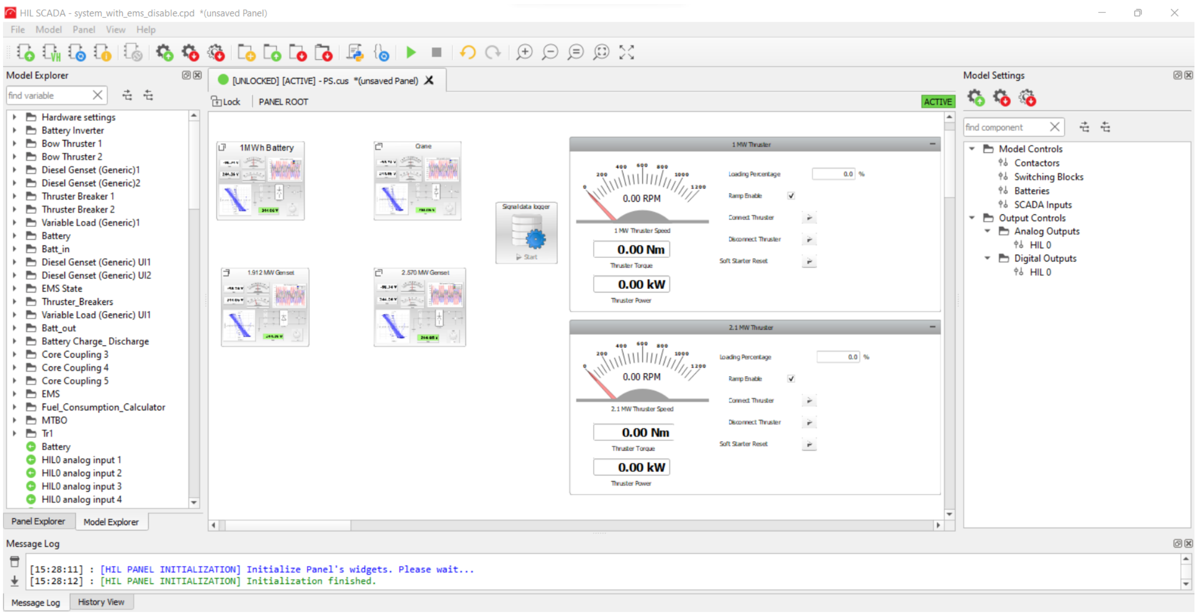


Figure 4.9: SCADA Dashboard for the Proposed Hybrid Vessel on Typhoon HIL

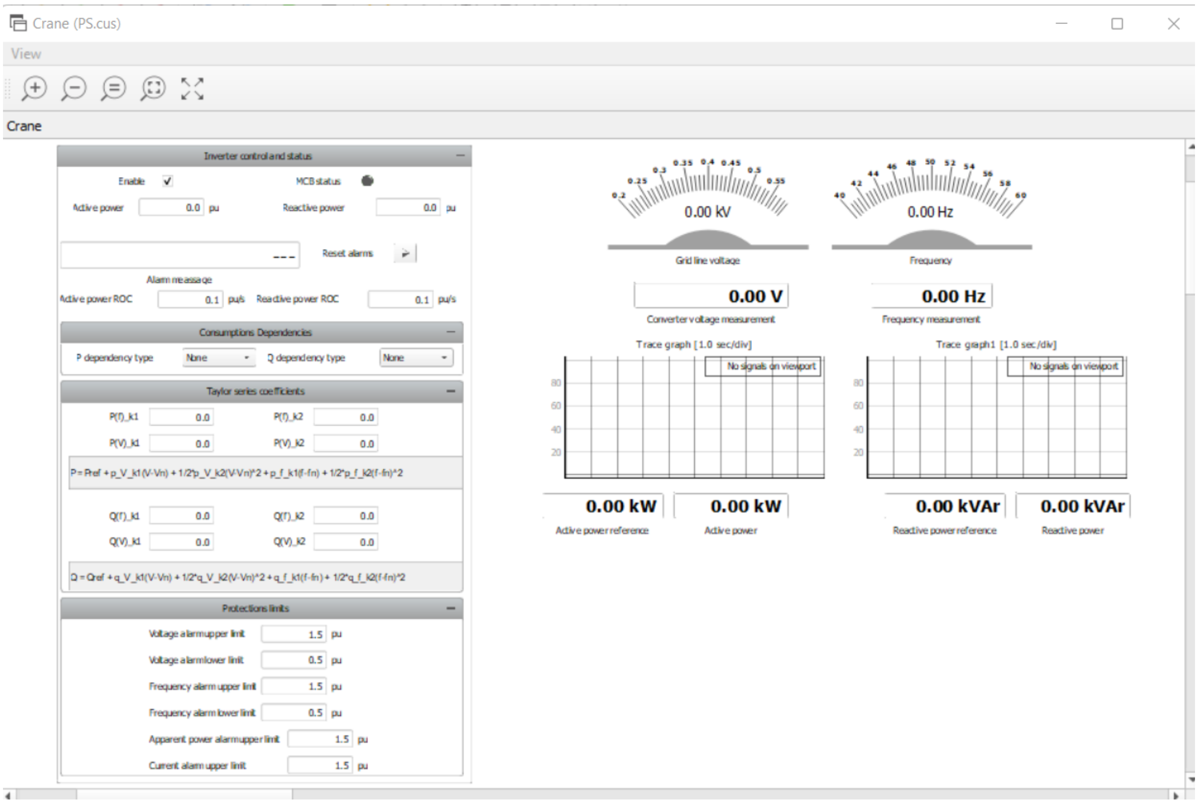


Figure 4.10: Crane on SCADA Dashboard

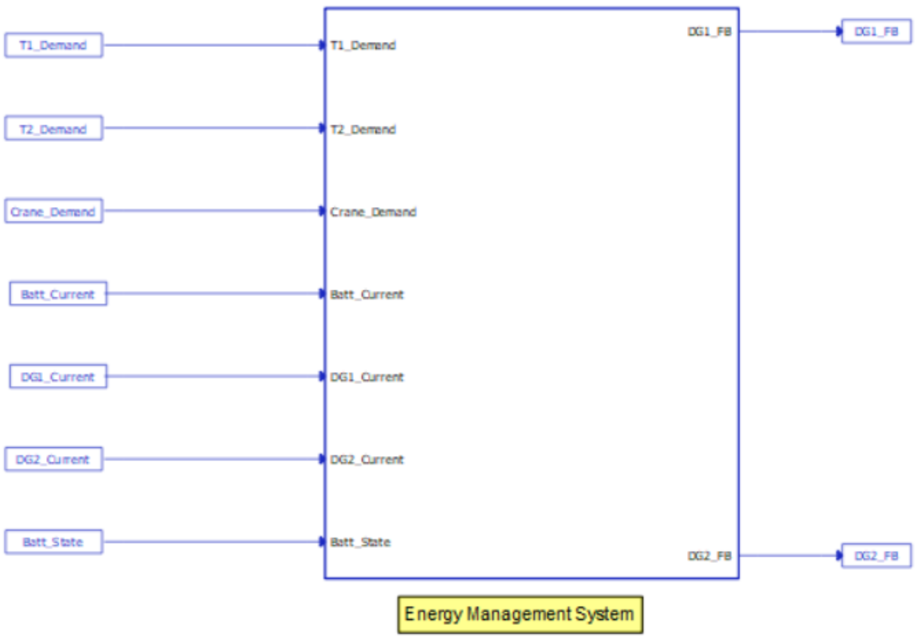


Figure 4.11: Modelled EMS Controller in Typhoon HIL

Summary of HIL 604 Machine Modelling Challenges

1. Improper core coupling tuning creates model stability issues.
2. Model stability issues include abnormal readings of grid voltage, inability of model to stabilize grid frequency with load changes, abnormal machine speed values (in negative value range).
3. Tuned model was stable on virtual HIL mode, but not in the real time simulation mode.
4. Improper tuning of core coupling components, can lead to large simulation timesteps. It is important to maintain simulation timestep in the range of microseconds to achieve the most efficient results.
5. The core coupling component can create a voltage difference in the grid, due to the placement of reactive elements in the component. This can create potential limitations to model stability, in various control related applications.
6. There was the need to use a combination of generic, average and switching components for the model, in light of computational limitations. The use of switching components for all energy sources and loads would require computation and memory, beyond the ability of a single HIL 604 device.
7. Implementation of Global Optimization Solutions is possible in the HIL system via python packages. However, the HIL system is developed such that python based scripts need to be placed in the SCADA platform. When the HIL system needs to make the complex calculations for the global optimization solution, and manage the update of rest of circuit and widgets on the testbed, the TSO flag is raised. This indicates that the calculations are too complex for the given timeslot of 250ms or 500ms or 1s. Therefore, it was not possible to implement algorithms such as the NSGA-II, Mixed Integer Linear Programming (MILP), Particle Swarm Optimization (PSO) and Model Predictive Control (MPC) to name a few.

This chapter has explored the entire model development process of the proposed hybrid vessel in the DP2 mode. Discussions into the modelling phase on the Schematic editor and SCADA panel development were conducted. Certain limitations and challenges with the HIL 604 machine was discussed. Chapter 5, will discuss how the EMS controller is developed and verify its working.

5
EMS Controller for the Hybrid Vessel

This chapter looks into the requirements to design and develop the EMS controller based upon the insights about the existing vessel, the hybrid vessel configuration and operational profiles. The verification of the EMS controller's working is also done based upon the potential load requirements, DG operational efficiency maximization and BESS integrity. For readers interested in the modelling of the vessel, please refer chapter 4.

5.1. EMS Controller Requirements

Based on the analysis from chapter 3, the EMS of the existing vessel needs to be modified in order to optimize the DERs in the grid. With the addition of the BESS on the Port Side and Starboard Side, the EMS will now need to make additional decisions to optimize the use of DGs, whenever the BESS is undergoing a charge cycle. A breakdown of the expected EMS tasks are described below:

- Optimize DG operation to reduce Specific Fuel Oil Consumption for different load profiles.
- Choose most optimal DG available, to reduce and minimize maintenance costs.
- Ensure integrity of the grid and maintain power balance.
- Ensure BESS Charge and Discharge is within recommended C-rates, as stipulated by the manufacturer.
- BESS charge and discharge should fall within the Depth of Discharge (DoD) limits and cycle lives provided by the manufacturer.

5.2. EMS Control Algorithm

From the previous sections, it is now clear the rule based algorithm needs to make the best decisions with respect to the usage of the DGs and BESS. For this model, it is decided that, to extend the BESS lifetime, a 50% Depth of Discharge is to be used. Additionally, as per the data that was made available from one of the BESS providers [39], the charge and discharge limits of the BESS is kept within 1C or 1000kW. Given the fluctuating load demands, more rules will need to be defined to ensure the BESS doesn't charge at a power greater than 1000kW. The defined control logic is placed as a flowchart in appendix A. The EMS controller needs to continuously monitor changes in the load demand from the vessel to make decisions. Therefore the set sampling rate is 2μs. This was achieved by designing the controller on Typhoon HIL's schematic editor using C language code.

5.3. EMS Testbed Development

This section discusses the results that were achieved during the test phase of the designed EMS. To test this controller for a variety of scenarios, an automated simulation testbed was designed. An automated testbed consists of loading the entire load profile beforehand into the HIL simulation environment, and then starting the simulation to observe the decisions by the EMS. The testbed automation was possible by means of the Dynamic Stimulation Model feature of Typhoon HIL. The model is depicted by figure 5.1. A limitation of this approach is that only a limited number of datapoints can be loaded beforehand as there is the risk of raising the TSO flag. The reason for this flag is because the HIL machine needs to memorize all datapoints of the different loads for the entire duration of simulation. Then, it needs to execute these exact loads at the exact defined timeframe. Therefore, for long duration tests in the order of hours to days, the large memory requirement is a shortcoming of this feature. The main advantage of this type of testbed is that the HIL device can continue to test your prototype, on it's own, requiring little or no human interference and removes repetitive tasks.

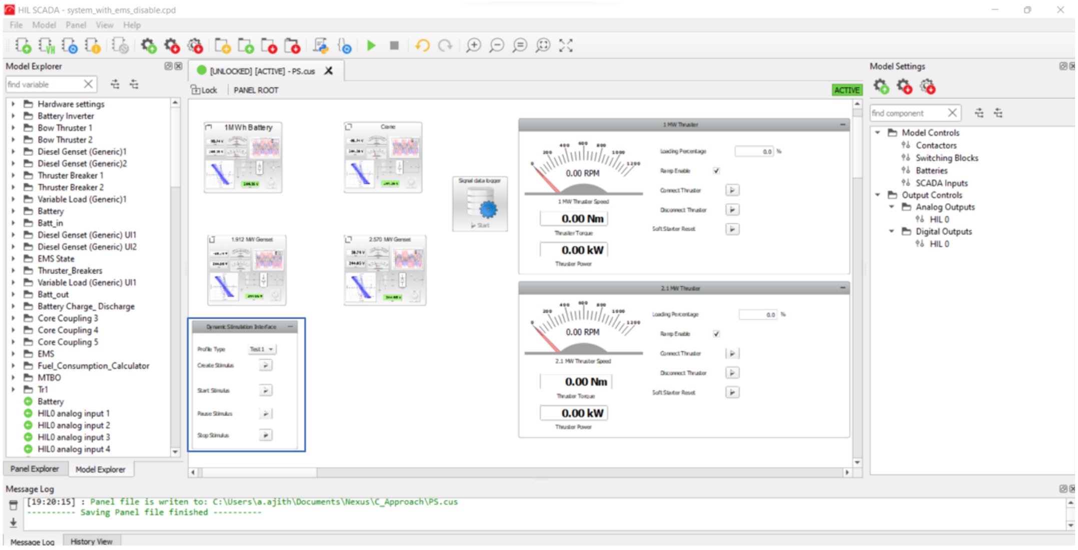


Figure 5.1: Dynamic Stimulation Model

In order to implement this testbed, the load profile length had to be limited. Therefore, it was decided to follow the approach taken by the United Nations Economic Commission for Europe (UNECE), for road vehicles, that is the New European Driving Cycle (NEDC). The NEDC test is a standard test all light duty vehicles need to undergo to ensure they meet European Commission (EC) environmental regulations [40]. The fuel consumption is calculated by the UNECE using a specific formula based upon the CO_2 emissions [40]. Therefore, it was decided to implement the loads on the Y-axis in place of the vehicle speeds as shown by the NEDC.

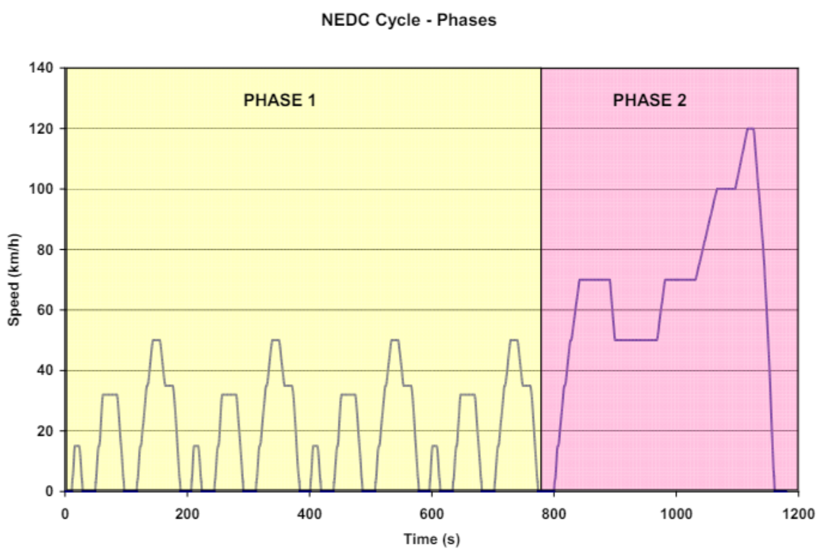


Figure 5.2: New European Driving Cycle [40]

As mentioned earlier, the objective of this section is to verify the working of the EMS control logic. The use if the Typhoon HIL Dynamic Stimulation model is made for automating the designed testbed. It is important to note for easing the computation requirements for the HIL device, **the data was logged every 10s** in the automated tests. Therefore, the ramp up and down of the DG1 and DG2 at 0.1 pu/s was at times missed. These tests were conducted based upon the range of loads the vessel is expected to experience in the Taiwan Strait and North Sea. Two cases in the simulations were considered. The first at a low battery state of charge and the second with a high battery state of charge. By this approach, it was possible to analyze the working of the EMS controller in both extreme cases. As mentioned previously, the primary objectives of the battery for this vessel are **to provide all electric operation, act as a spinning reserve, provide peak shaving and load levelling services**. For more details into the definition of these roles, please refer section 3.5.1. Additionally, as mentioned earlier, the BESS will not be allowed to charge or discharge any energy above 1C or 1000kW.

5.4. Automated Tests for Taiwan Strait and North Sea Load Profiles

5.4.1. Taiwan Strait Load Profile Starting with Low Battery State of Charge

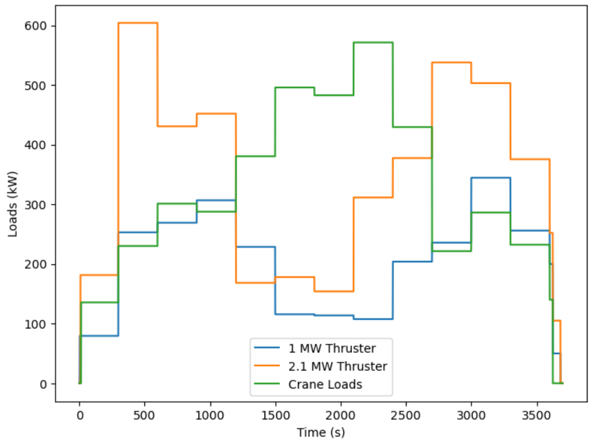


Figure 5.3: Load Profile at low Battery SoC

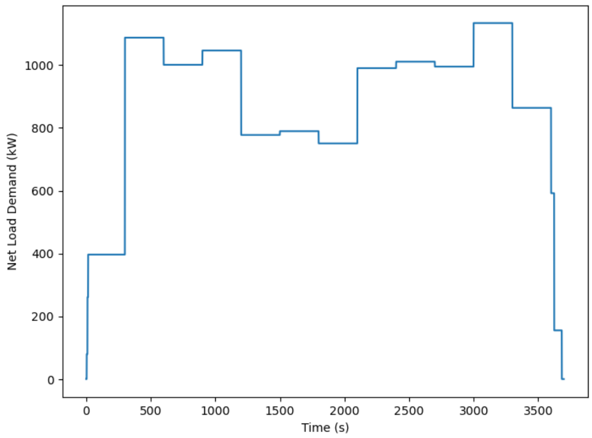


Figure 5.4: Overall Load Profile at low Battery SoC

Figures 5.3 and 5.4 show the simulated loads of different energy consumers and the net consumption respectively. For this case, two peaks exceeding the 1000kWh mark are simulated, with relatively high load demands in the range of 400-1000kW in the entire cycle. As shown the figures 5.5 and 5.6, it can be noted that DG1 was brought online to meet the energy demand and charge the battery, once it reached an SoC of 30%. DG1 continues to operate and meet the load demand and battery charge power until the end of the test cycle. In practice, the system should continue to charge the BESS until it reaches an SoC of 80%. It was possible to operate this entire cycle, with only DG1 in operation, DG2 remains on standby throughout the process. DG1 was also able to achieve a relatively high loading % that ranged between 68% and 75% and is subject to change with the load demand fluctuations.

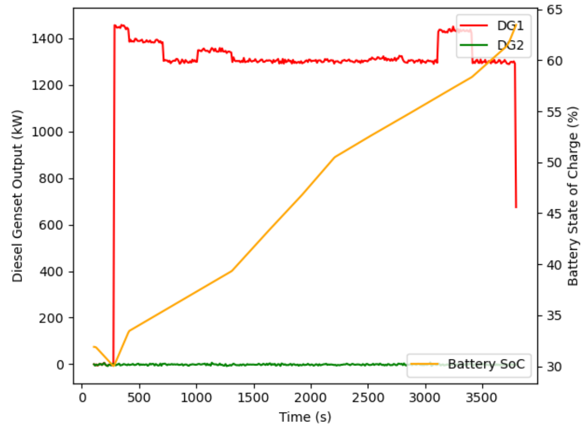


Figure 5.5: Overview of Performance by DER on the Grid

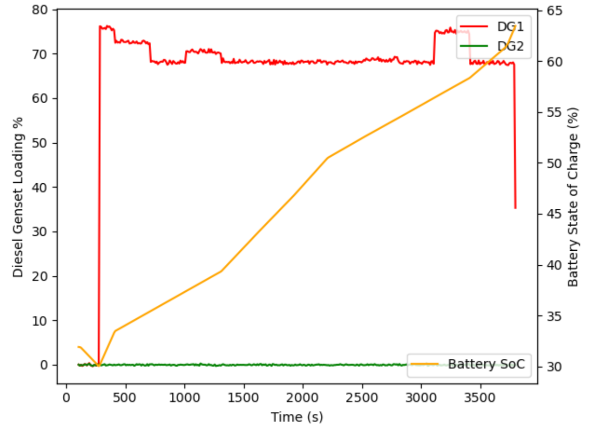


Figure 5.6: Operational DG Loading %

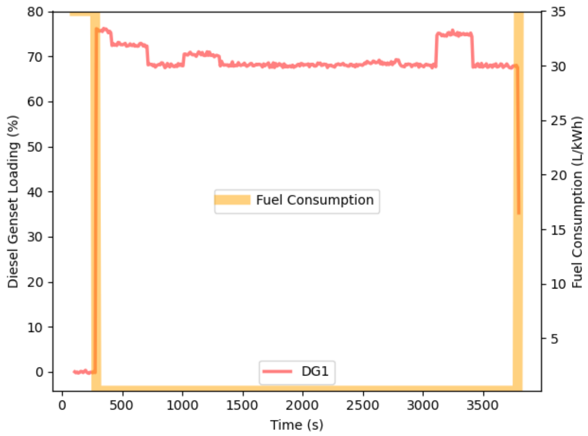


Figure 5.7: Fuel Consumption at Different DG Loading %

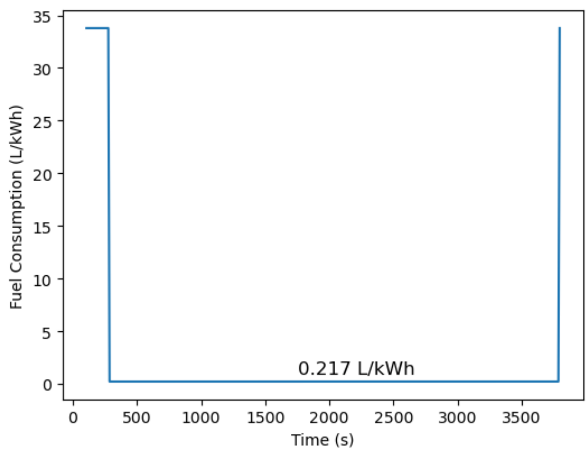


Figure 5.8: Fuel Consumption Change

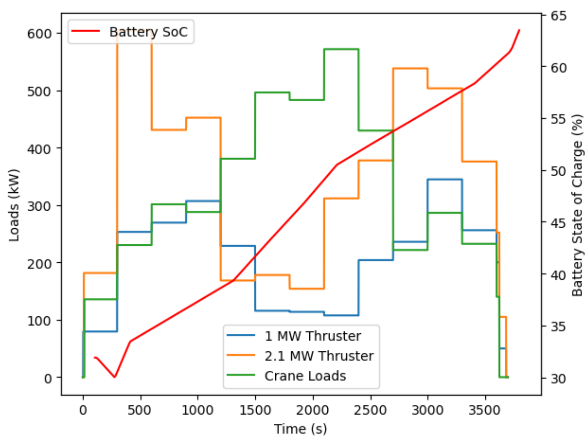


Figure 5.9: Battery Cycle with Loads

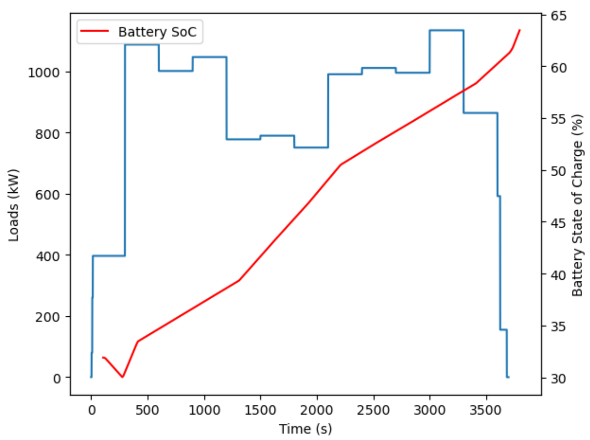


Figure 5.10: Battery Cycle with all Loads

The change in fuel consumption as the DG attempts to meet the load demand is indicated by figure 5.7 and figure 5.8. **As the DG1 now operates in a high efficiency region with an average loading factor**

of 70%, the specific fuel oil consumption decreases to about 0.217 L/kWh. DG2 remains on standby and consumes the standby mode fuel demand that is approximately 10 L/hour. Figure 5.9 and figure 5.10, indicate the performance of the battery with how the entire loading profile changed throughout the cycle. There have been stages wherein the battery charge rate was a bit lower than the set target of 1C or 1000kW. This is because it is not feasible to operate DG2 to meet the additional load demand, as it would be a non-optimal loading point, which undoes the purpose of optimizing the DG loading factor. Therefore, at the end of the simulation, the BESS reaches an SoC of 65%. If the simulation continued longer, the system should have run until the BESS reached an SoC of 80%.

5.4.2. Taiwan Strait Load Profile Starting with High Battery State of Charge

In this section, the same test was conducted, except the simulation was started with a high battery state of charge at 95% SoC. This additional energy is assumed to have been made available to the battery from a shore connection. Figures 5.11 and 5.12, indicate the load profile that was simulated. Two peaks greater than 1000kW, with loads ranging between 400-1000kW was simulated.

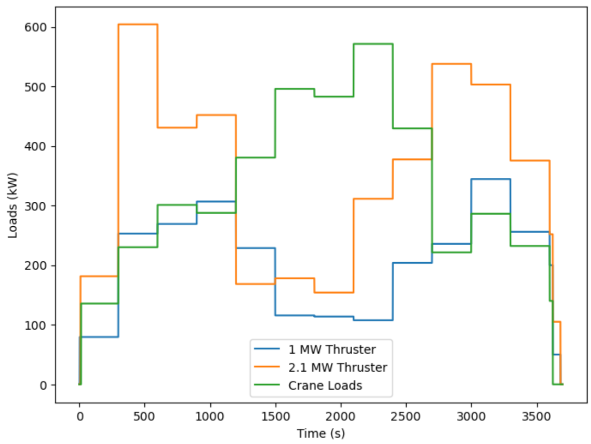


Figure 5.11: Load Profile at high Battery SoC

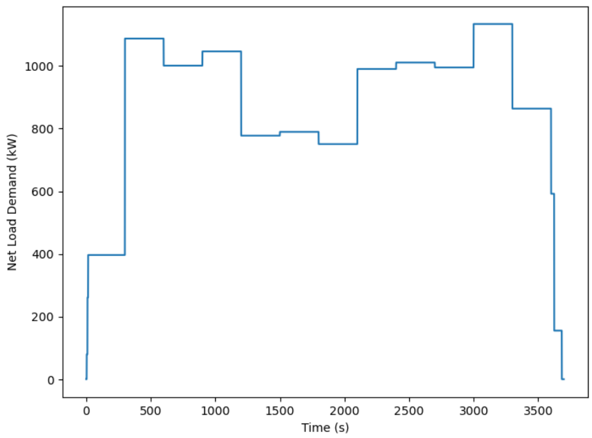


Figure 5.12: Overall Load Profile at high Battery SoC

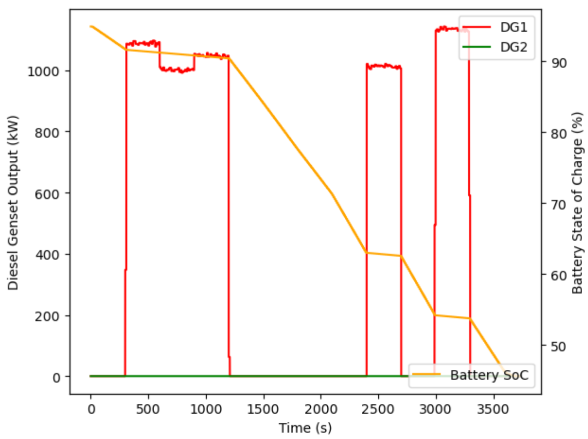


Figure 5.13: Overview of Performance by DER on the Grid

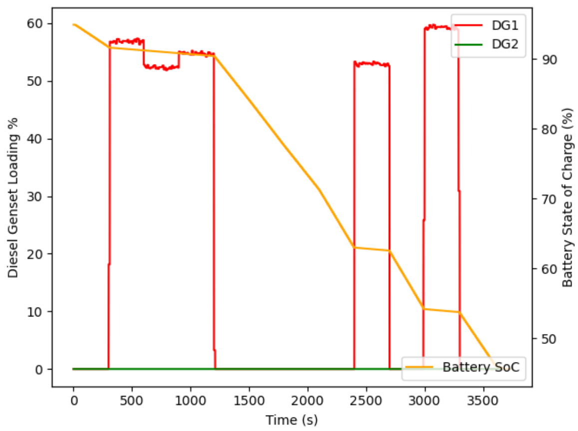


Figure 5.14: Operational DG Loading %

From figures 5.13 and 5.14, it can be noted that the BESS performs all electric mode operation. Whenever the load demand is below the set threshold of 1000kW, the BESS discharges to meet energy demands. In the event, the load demand exceeds the 1000kW mark, as seen in the load profile, DG1 enters into operation to meet the load demand. Thus, the BESS, does not meet load demands that have exceeded 1000kW. However, there is a small 50kW loss experienced by the power converter, as a result of which there is a very small discharge from the BESS during DG operations. This loss is most likely due to the the core coupling component placed in the Typhoon HIL system. In this case, since the loads were just above 1000kW and less than 1100kW, DG1 was loaded in the range of 55% - 62%. This is also one possible eventuality that needs to be accepted for DG1, as DG2 would not operate at an optimal loading point at this load demand. It is also important to note that for this cycle, the entire operation was covered with DG2 remaining on standby.

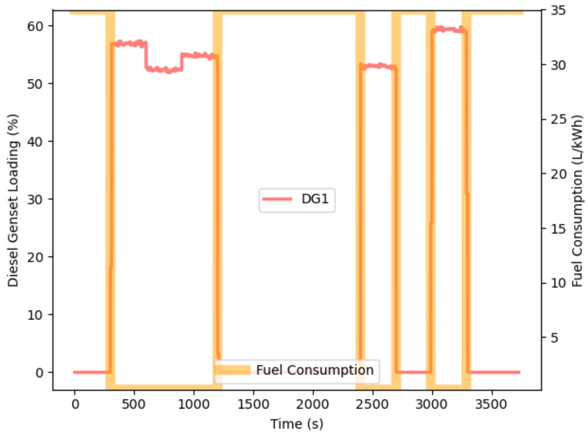


Figure 5.15: Fuel Consumption at Different DG Loading %

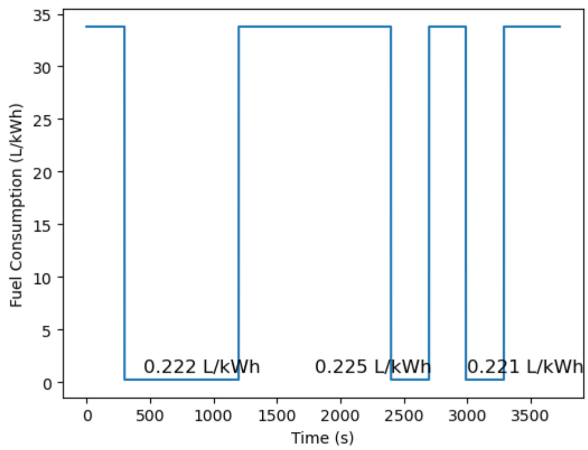


Figure 5.16: Fuel Consumption Change

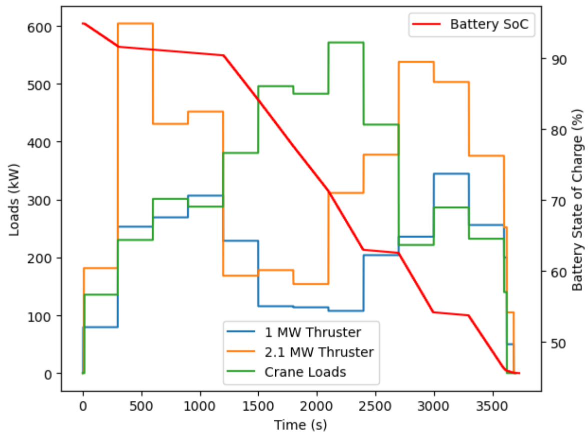


Figure 5.17: Battery Cycle with Loads

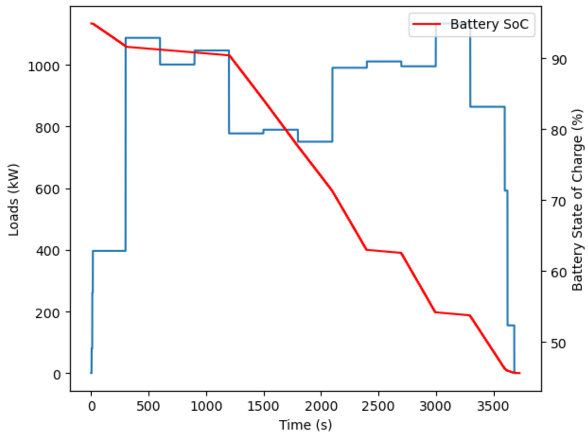


Figure 5.18: Battery Cycle with all Loads

From figures 5.15 and 5.16, the change in fuel consumption as a result of meeting the the load demand by DG1 can be seen. **DG1 moves from a high specific fuel consumption region to the range of 0.22 L/kWh**, which is of higher fuel consumption efficiency. In figures 5.17 and 5.18, the operation of the entire load profile with the changes in the BESS SoC can be visualized. For this design of the profile, the system approximately reaches an SoC of 48% at the end of the simulation. Nevertheless, the EMS controller ensures that BESS operates within the desired discharge limits that have been set and the DGs are able to arrive online and meet power requirements as and when required.

5.5. Automated Tests for North Sea Load Profiles

5.5.1. North Sea Loading Profile starting with Low Battery State of Charge

In the case of the North Sea, given the seas are much more chaotic, the load demand in the DP2 mode can be significant at times. Therefore, to verify the controller, load demand up to 3000kW was tested, as this was the specified load range from the measurement data provided by the vessel operator. Figures

5.19 and 5.20 represent the designed load profile. From figures 5.21 and 5.22 and 5.23, it can be noted in this case that as the load profile keeps changing, there is the need for operation of DG1 and DG2. In the initial stage, DG1 met the load demand and was charging the battery. However, as the load demand progressed further and exceeded the optimal operating point of DG1 that is approximately 1430 - 1550 kW, DG2 entered operation to meet the load demand.

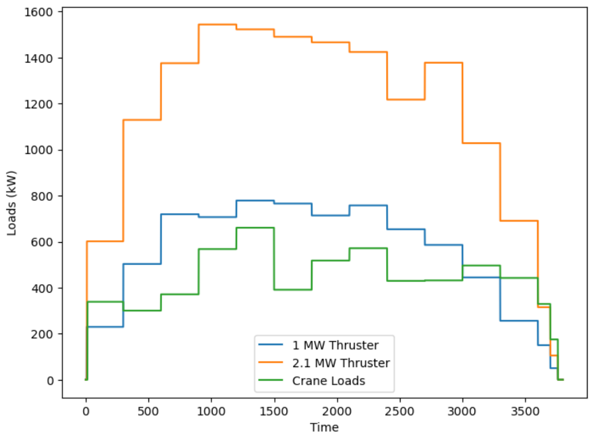


Figure 5.19: Load Profile at low Battery SoC

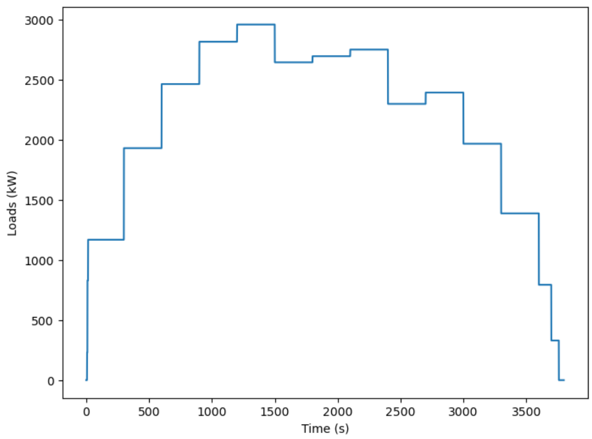


Figure 5.20: Overall Load Profile at low Battery SoC

As can be seen from the figures 5.22 and 5.23, both the DGs operated at an optimal loading point of about 75% for most of the time, depending upon the fluctuating load demand. Although the BESS reached the 80% SoC by about 3000s, it does not actively discharge until the load demand decreased below 1000kW. By that metric, the EMS has ensured that both DGs operate at a high loading point and at the same time, ensured the BESS charges and discharges within set limits.

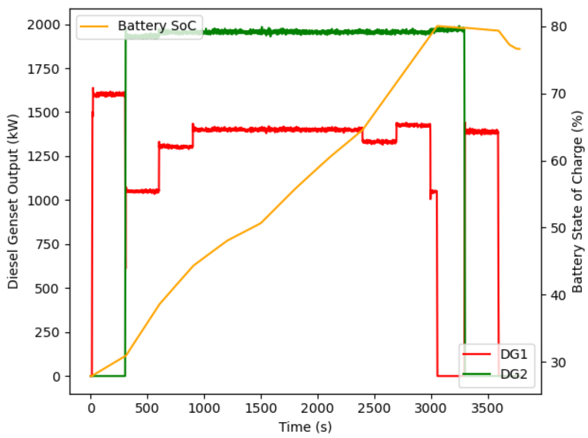


Figure 5.21: Overview of Performance by DER on the Grid

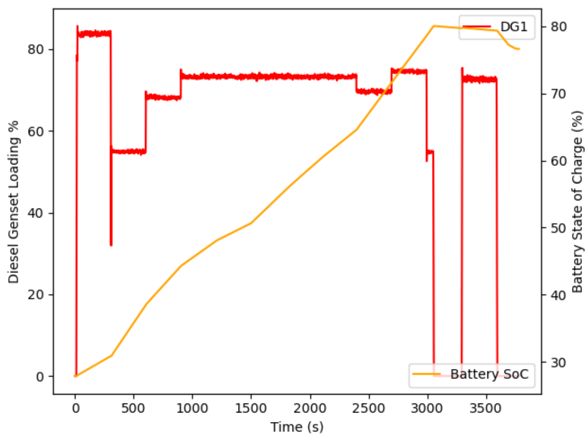


Figure 5.22: Operational DG1 Loading %

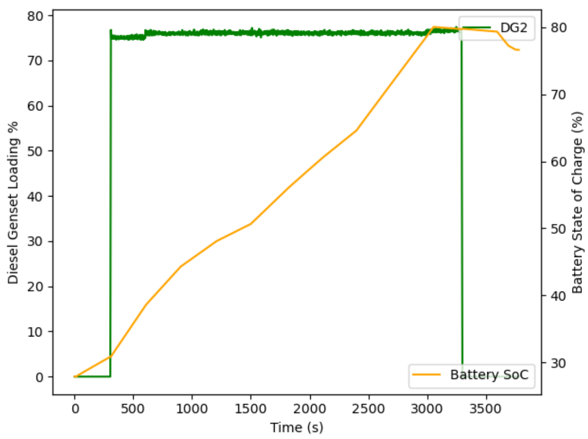


Figure 5.23: Operational DG2 Loading %

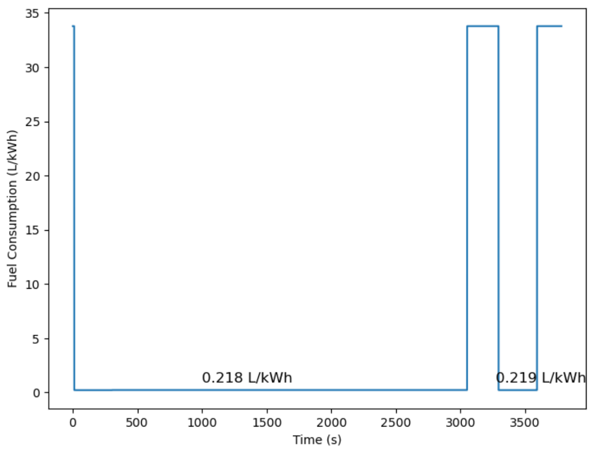


Figure 5.24: Fuel Consumption DG1

The fuel consumption also declines with the changing loading percentage of the DG. As illustrated by figures 5.22 and 5.23, **the specific fuel oil consumption decreases to 0.218 L/kWh and 0.214 L/kWh for DG1 and DG2 respectively**. The rate of charging the battery was kept under the set limit of 1C. As illustrated by figure 5.26, it can be seen that the battery charges almost linearly throughout the cycle, however, once the loads reach closer to the 3000kW range, there is a decrease. This is because the EMS is modelled to treat all loads of the vessel to be critical loads. The battery recharge load is considered to be non-critical. Therefore, in this case, the power supplied to charge the battery can range anywhere between 100-500 kW. Once the loads have declined to less than 1000kW, both DGs enter standby mode and the BESS continues it's fully electric operation activity.

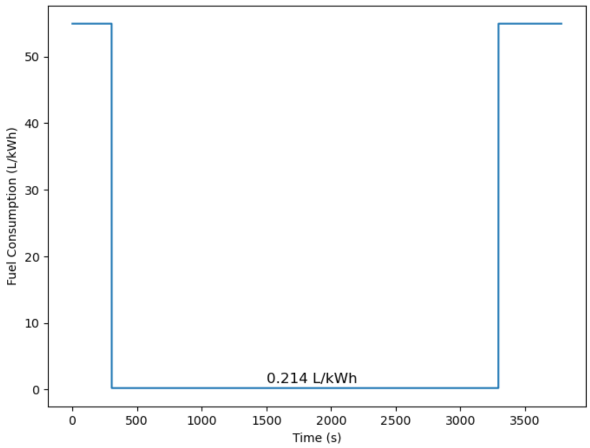


Figure 5.25: Fuel Consumption DG2

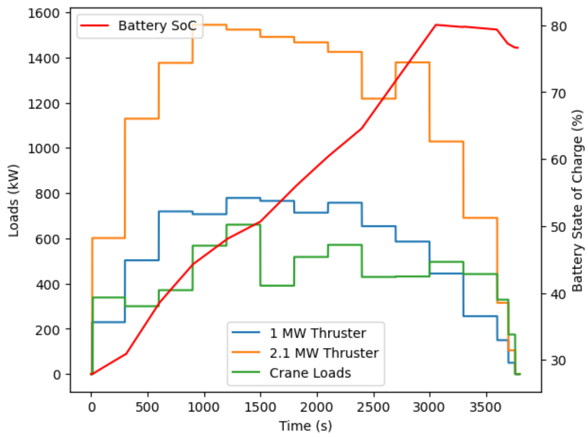


Figure 5.26: Battery Cycle with Loads

5.5.2. North Sea Load Profile starting with High Battery State of Charge

In this section, the same load profile test was conducted, however with a high battery SoC at 95%. Similar to the study under the Taiwan Strait high battery SoC case, it is assumed that this excess 15% energy was derived from shore power and therefore 95% is the SoC at the start of simulation. Figure 5.29 shows the overview of how the DERs on the grid interacted with the load demands. As indicated by the figure, DG1, DG2 and the BESS were used to meet energy demands. In the initial stages, since the loads were lower than the optimal loading point for DG2 which comes close to 1800kW, DG1 and the BESS were discharging energy to the grid. The EMS ensured that the DG1 operated at an optimal loading point for itself depending upon the load in combination with the BESS. As the load demand increased further beyond 1800kW, DG2 entered into operation and with the assistance of the BESS, maintained a steady operational loading point of 75%. The BESS here has assisted in the load levelling process.

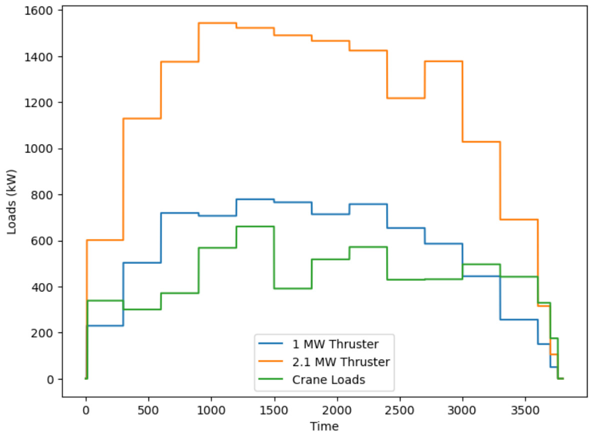


Figure 5.27: Load Profile at high Battery SoC

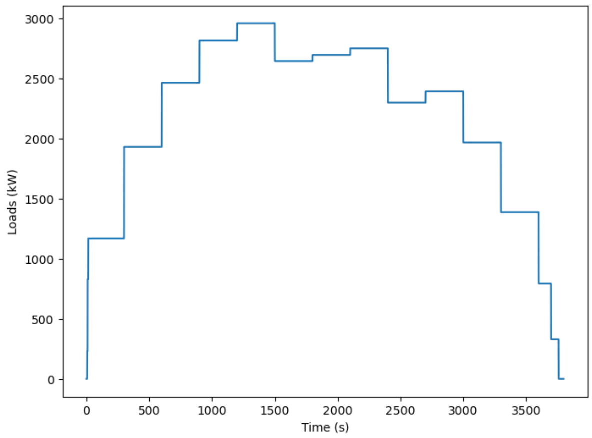


Figure 5.28: Overall Load Profile at high Battery SoC

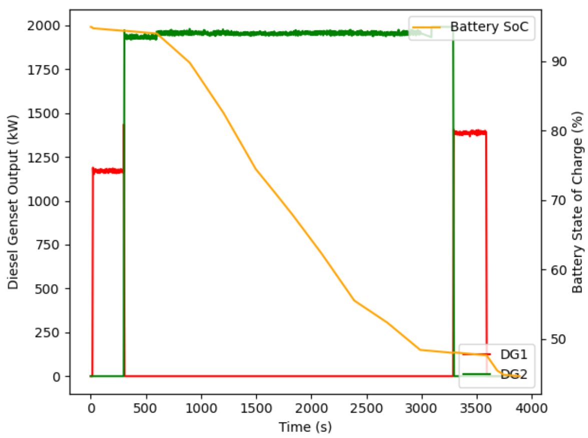


Figure 5.29: Overview of Performance by DER on the Grid

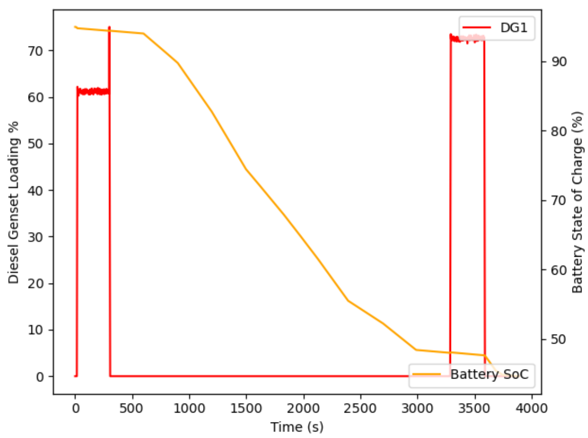


Figure 5.30: Operational DG1 Loading %

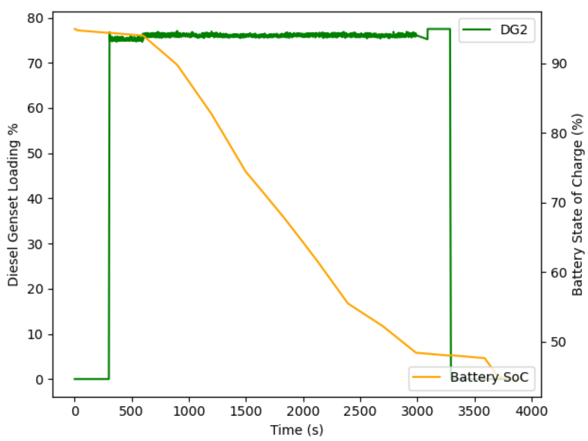


Figure 5.31: Operational DG2 Loading %

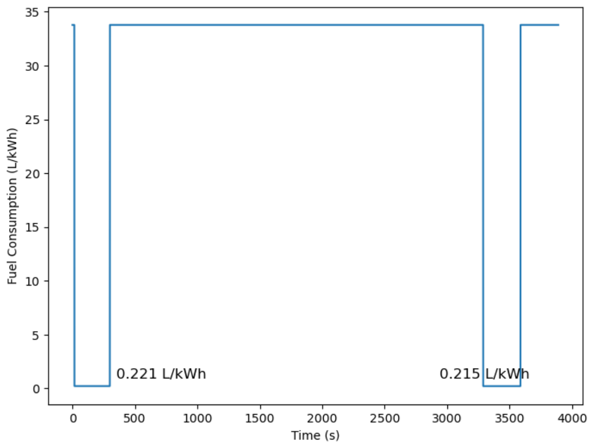


Figure 5.32: Fuel Consumption DG1

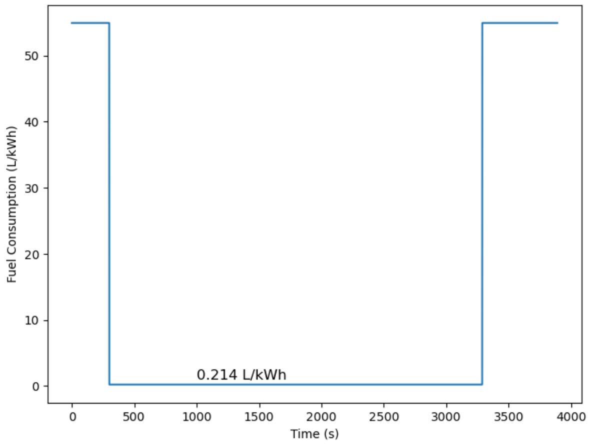


Figure 5.33: Fuel Consumption DG2

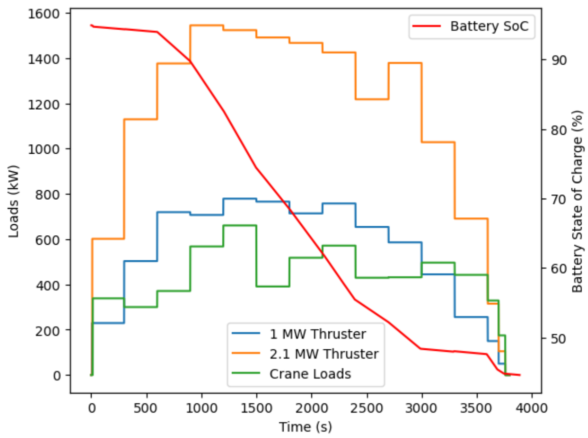


Figure 5.34: Battery Cycle with Loads

The DGs when in operation, operated at a specific fuel consumption of **0.22-0.21 L/kWh and 0.214 L/kWh for DG1 and DG2 respectively**. Overall, it can be seen that the BESS performs the function of peak shaving and load levelling from as seen on figure 5.34.

This chapter has analyzed the requirements of the EMS controller and verified the functionality on the Typhoon HIL platform. Chapter 6, will discuss how the designed EMS would work in the real world load data scenario.

6
Long Duration Tests

From the chapter 5, the working of the EMS was verified on the basis of different loading points. This chapter deals with implementation of the real time data of the vessel into the Typhoon HIL environment for real time simulation result extraction. These tests have been conducted on a long duration basis. The main objective of this test is to understand how the EMS would control the vessel in the real life setting with actual vessel load profiles.

6.1. Long Duration Tests

The objective of this section is to implement the vessel operational load demand data into the proposed hybrid vessel configuration in Typhoon HIL. This section will also look into the expected fuel consumption and savings, maintenance savings and emissions. This section will also look into some additional observations and suggested improvements implemented for the EMS.

6.1.1. Test 1 - Most Probable Load Demand Scenario in DP2 mode

The estimation of fuel savings, emission reduction and maintenance savings is heavily dependent on the operational profile, the duration of operation, BESS SoC at start of simulation and the EMS control strategy. In order to consider the need to charge the BESS at the start of operation, the test was modelled starting at a low initial SoC of 30.5%.

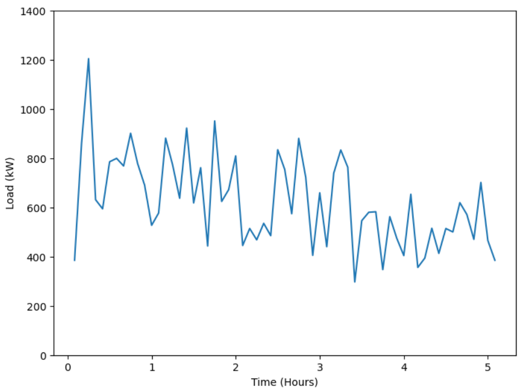


Figure 6.1: Original Load Data from Vessel

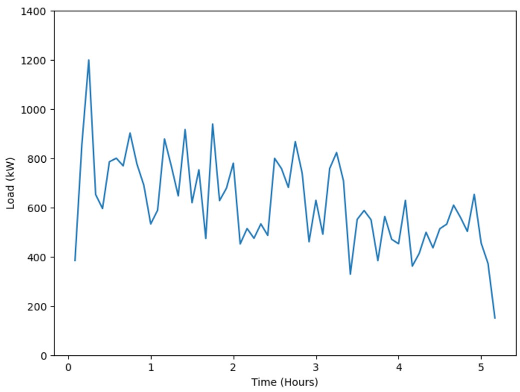


Figure 6.2: Simulated Load Data in Typhoon HIL

Figure 6.1 was selected from the Vessel's operations in the DP2 mode. The selection is based of the data that was seen for the vessel operations, in the Taiwan Strait and North Sea from chapter 3. It is acknowledged that this profile is assumed to be the most likely operational scenario for the entire year. There can indeed be deviations from the exact operation on sea in the future. This is attributed to the fact that road vehicles where speeds (main load) are moderated by traffic control. The vessel load demand in DP2 mode is subject to weather pattern shifts, temperature, waves speed, wind speed and the depth of operation that is demanding power. Therefore, for simplicity in calculations and estimation of savings, it is assumed to be the most common load profile. Figure 6.2 shows the simulated load profile of the hybrid vessel in Typhoon HIL. The simulated version in the long duration test is conducted through human control, since the test runs longer than 1 hour. The operation has been made to mimic the actual vessel as closely as possible.

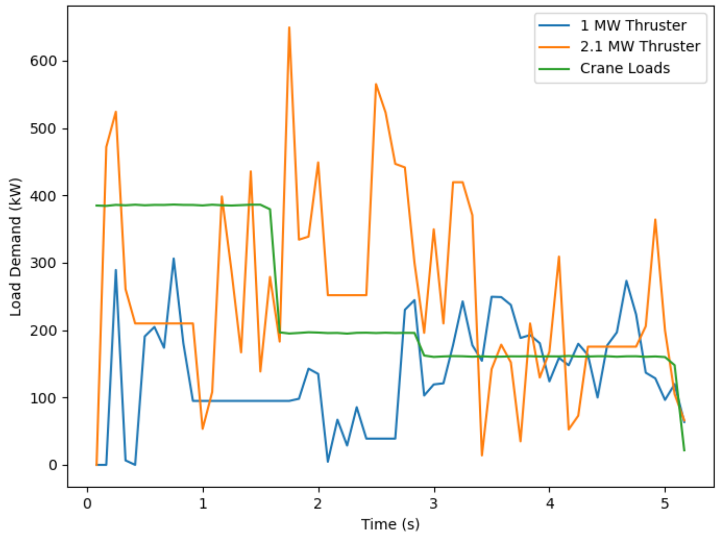


Figure 6.3: Vessel Operation Energy Consumers

Figure 6.3 shows the main energy consumers for the vessel operation. The thrusters are in complete operation throughout the simulation due to uneven waters, and the need to reposition the vessel at it's desired coordinates. However, the operational profiles of the now hybrid vessel has changed as illustrated below in figure 6.5.

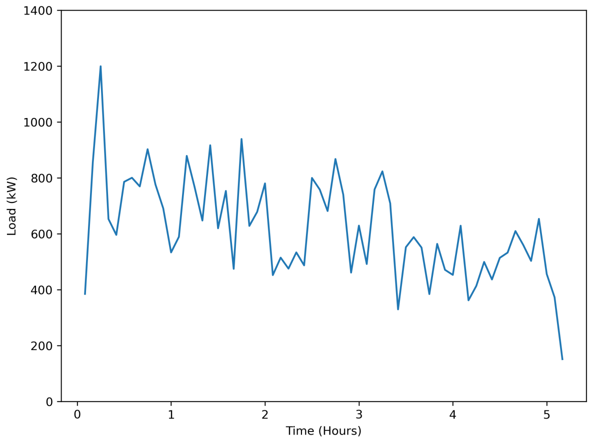


Figure 6.4: Simulated Load Data in Typhoon HIL

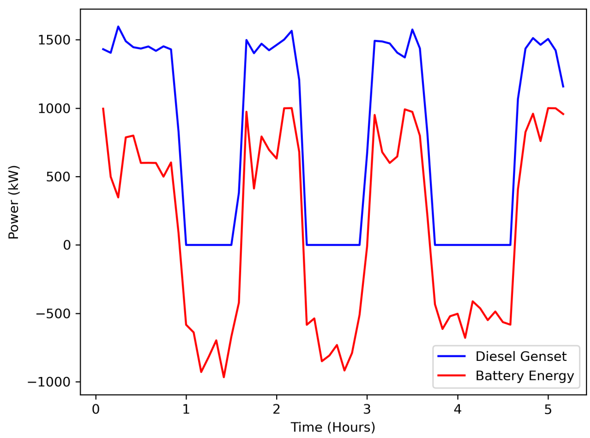


Figure 6.5: The operation of the Hybrid Vessel by EMS

Figure 6.6 shows the detailed overview of the new operational profile of the vessel under optimized control. As indicated by the arrow in figure 6.7, it can be seen that the additional energy produced by DG1 against the existing vessel load demand goes towards the BESS charge phase. It is also noted that the BESS charge and discharge is limited to under 1C throughout the cycle. Once the BESS has reached the set SoC limit of 80%, the BESS meets load demand, as long as the loads lie below 1000 kW. This additional power delivered enables the DG to operate in the low SFOC region as validated by the EMS controller in chapter 5. The effect of this is discussed in the following stages of this report.

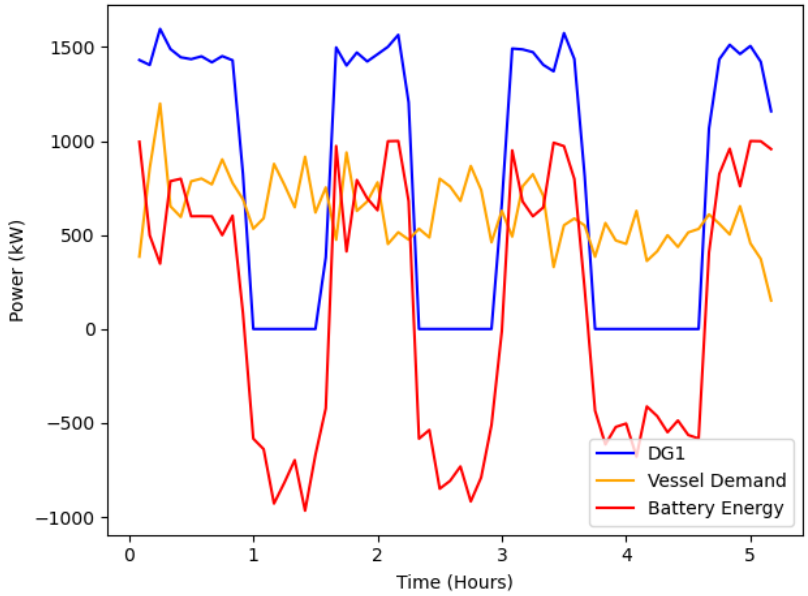


Figure 6.6: The New Operational Profile

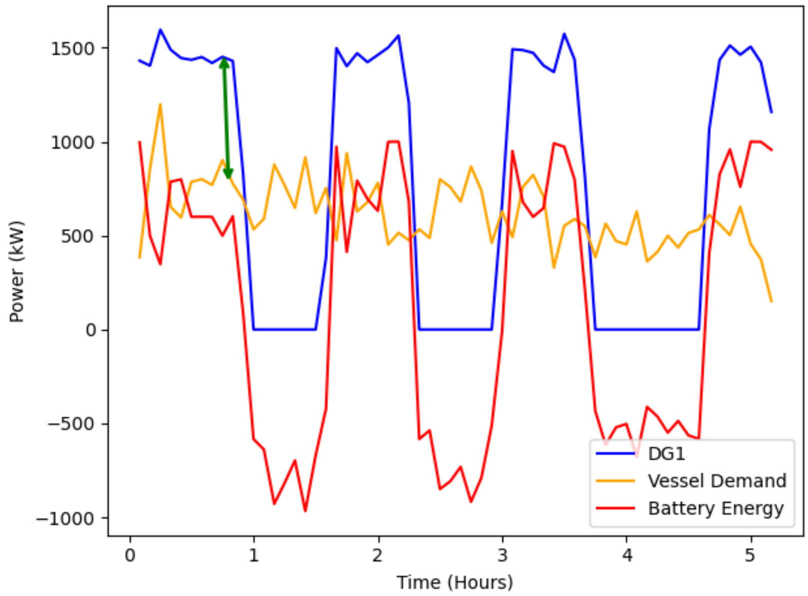


Figure 6.7: Closer Look Into New Operational Profile

The regions in figure 6.5 that are in the negative scale indicate energy discharge by the BESS. By that process, it was possible to avoid operating the DG at a non-optimal loading point less than 50% of it's rated capacity. However, now there is an additional load to the vessel namely the BESS when undergoing charge. So while the BESS undergoes charge, given that there are no renewable energy sources onboard, the DGs will consume fuel for this demand to be met.

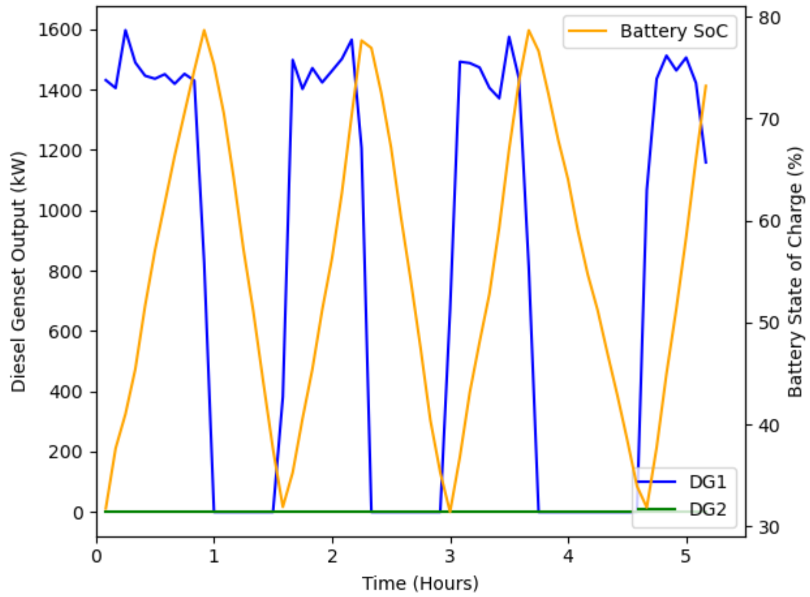


Figure 6.8: The overview of the performance of the DER in the hybrid vessel

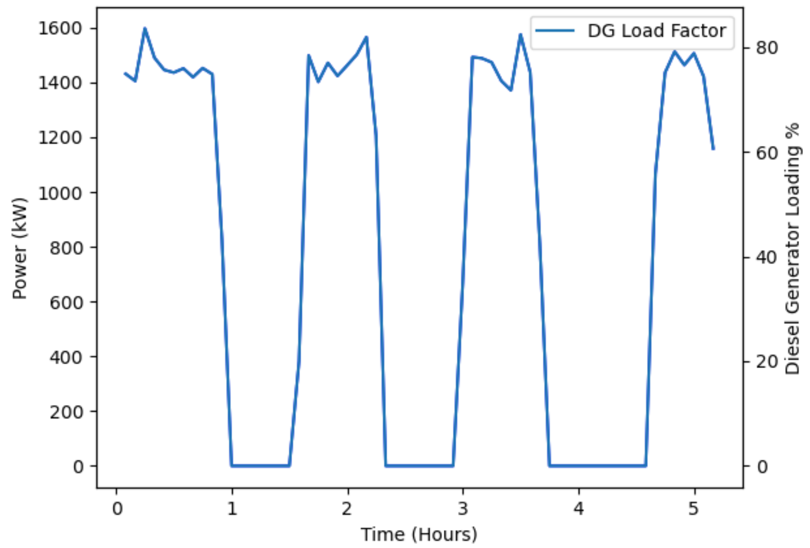


Figure 6.9: The loading of the DG in the new load profile

As illustrated by this operation in figure 6.8, it is possible to operate the most probable average load profile of this vessel, with DG1 alone in combination with the BESS. DG2 can remain on standby for the entire operation, thereby preventing it's operation in an undesirable loading point. On average, the BESS would complete 3 cycles at a set Depth of Discharge of 50%. The SoC limits and DoD have been controlled as designed by the EMS controller. Finally, on figure 6.9 it can be seen that DG1 consistently operates in a high loading region between 70% and 80%.

6.1.2. Test 2 - High Load Demand Scenario in DP2 mode

This section aims to discuss the simulation results of the hybrid vessel in a high load demand scenario. This dataset was procured from the North Sea operational profile of the existing vessel and displayed by figure 6.10. The simulated vessel load demand profile in the hybrid vessel, is depicted by figure 6.11. This test was conducted starting the simulation at low initial SoC of approximately 30.5%.

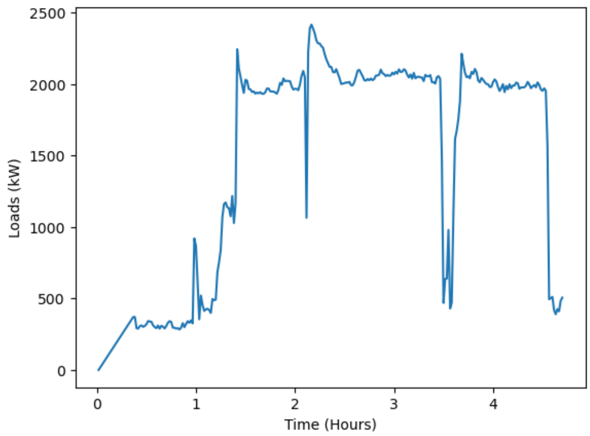


Figure 6.10: Original Load Data from Vessel

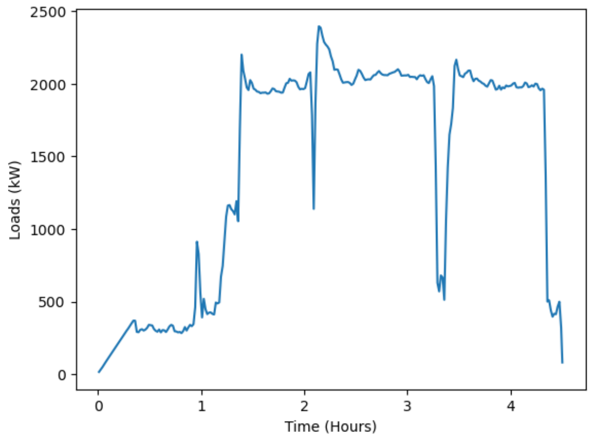


Figure 6.11: Simulated Load Data in Typhoon HIL

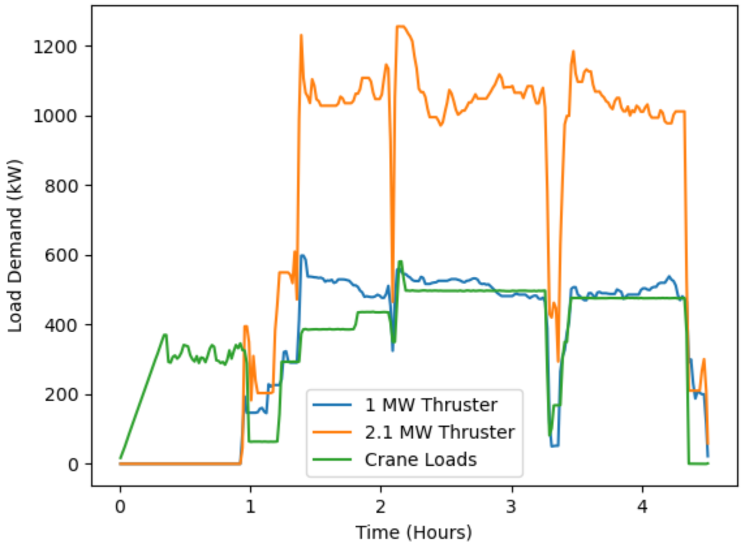


Figure 6.12: Vessel Operation Energy Consumers

Similarly, in this high load event scenario, the 2.1MW thruster is maintained in operation, along with the 1MW thruster for the entire operational cycle. This is due to the probability of wild seas experienced by the vessel in the North Sea. At the same time, the load profile has changed in this operation whenever the battery undergoes charging. Therefore, hybridizing the vessel implies a change in the load profile during times of low energy available in the BESS.

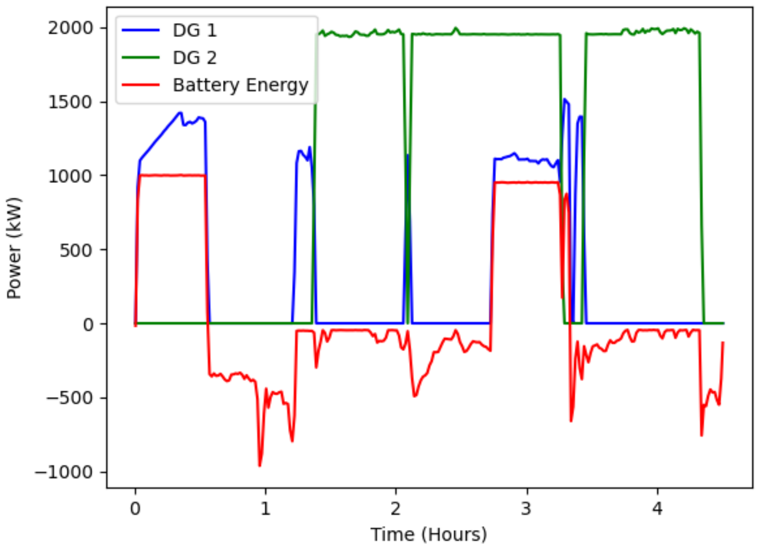


Figure 6.13: Overview of the DER Operation

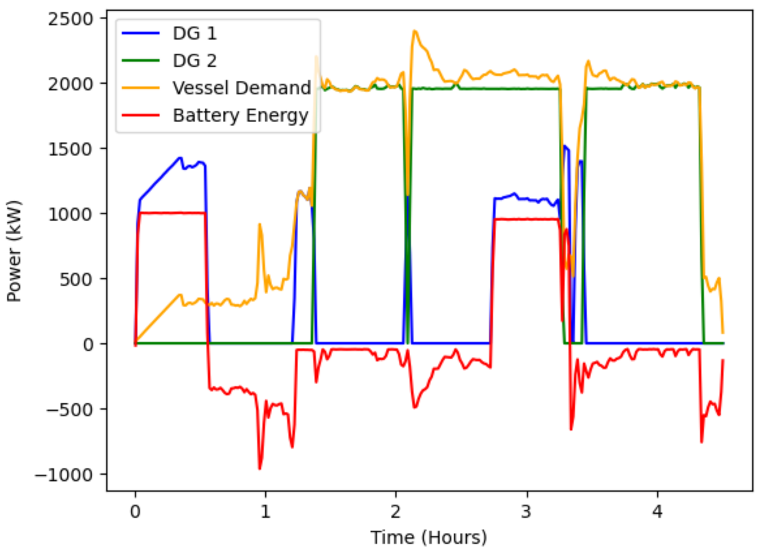


Figure 6.14: Overview of the DER Operation with Vessel Operation Load Demand

For this operation phase, the load demand for operating the vessel remains consistently high at over 2MW in the operation phase. The regions wherein the Battery Energy is in the positive, indicates the charging phase of the BESS, while negative regions indicate BESS discharge phase. Within the 1st hour of operation, given the load demand was consistently below 1000kW and BESS undergoing charge for the first thirty minutes, DG1 was in operation in this phase until the BESS reached the threshold of 80% SoC. Upon reaching the set threshold, the BESS operates in all electric mode to meet the load demand. This continued until the vessel load demand was below the set threshold of 1000 kW. Shortly after the first hour, the load demand exceeded 1MW but was below 1.5MW. Therefore DG1 was in operation, as the BESS cannot discharge above 1C and this demand was optimal for DG1 and non-optimal for DG2. However, the load demand progressed further and reached within the range of about 2MW. Therefore for DG2, this comes to a value of an optimum loading point of 76%. Any excess energy demand is met by the BESS as depicted by figures 6.13 and 6.14 respectively. Essentially now the BESS is assisting DG2 in load levelling, to ensure DG2 can continue to operate as efficiently as possible. During the period wherein the BESS reached the minimum SoC threshold of 30%, DG1 enters into operation in parallel with DG2. DG2 continues to operate in it's existing ideal operational loading point of 76%. Whereas DG1 produces sufficient power to charge the BESS and meet any of the peaks outside DG2's efficient zone. DG1 now works on the task of BESS charge and load levelling. Thereby it was possible to operate both the DGs in their high efficiency region, for most of the operation, as the load demand was consistently high. Therefore the EMS has ensured the efficient operation of the DGs and BESS as and when the loads changed.

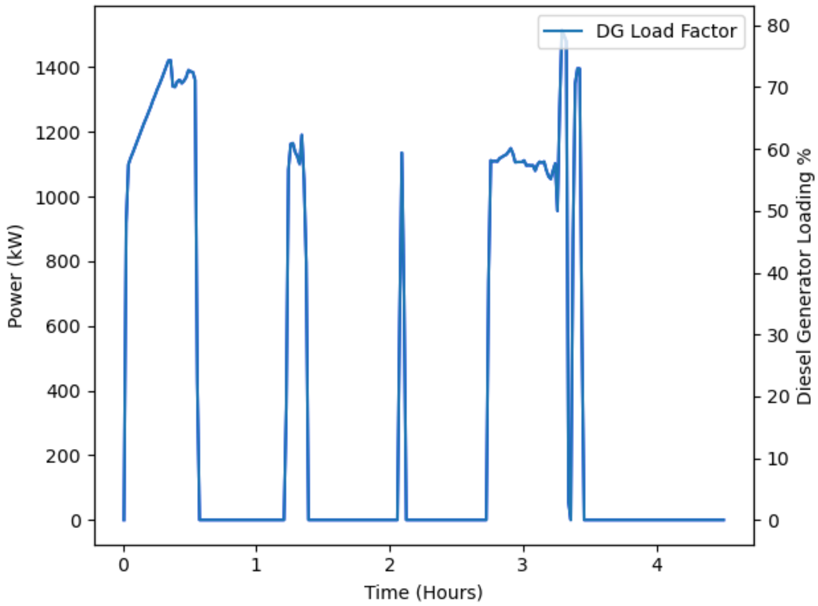


Figure 6.15: The Loading of DG1 during it's operation

As seen on figures 6.15 and 6.14, it can be noted that DG1 has mostly had the role of load levelling and charging the BESS in this operational profile. As a result, there were intermittent periods of short term operation of DG1 as the load demand fluctuated. On average, DG1 was operated between 60% and 75% as vessel load demand and BESS charge power request changed. DG2 as seen on figure 6.16, operated consistently between 70% and 80%. There were very short periods of non-operation and this is subject to the changing sea conditions and power demand from the thrusters. From figure 6.17, it can also be seen that the dependency on the BESS has been reduced greatly in comparison to the test from the most probable load demand scenario. Given the high load demand and limitations to the operation of the BESS, it only makes sense to use the DGs to meet this demand. Thereby, the EMS has also met the condition to maximize the operation of the DGs at high loading instances with reduced dependency on the BESS. There were instances wherein operating DG1 was not efficient. At those times, DG2 and BESS worked in parallel to maximize efficiency.

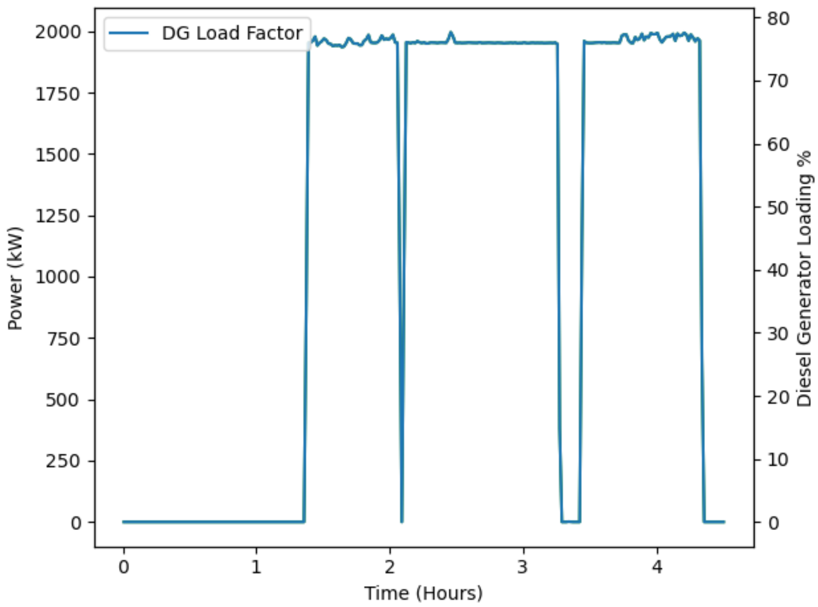


Figure 6.16: The Loading of DG2 during it's operation

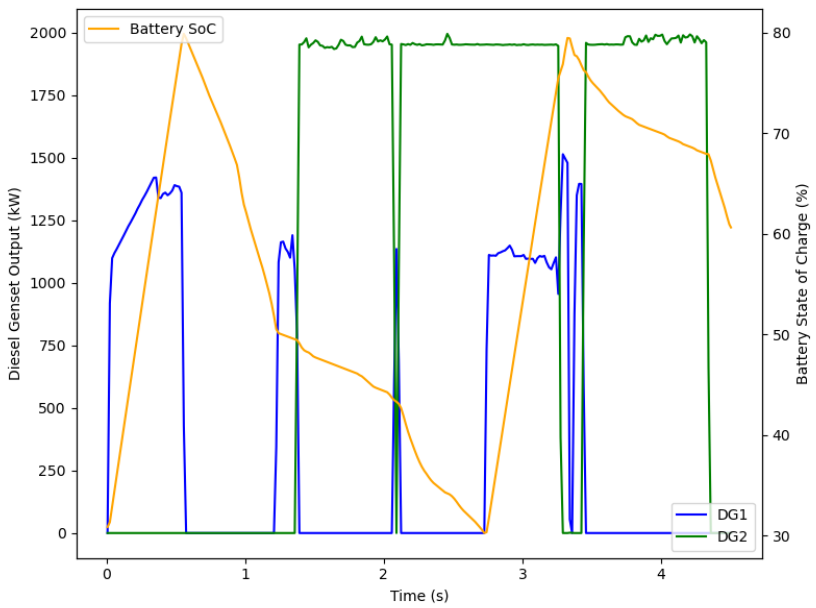


Figure 6.17: Overview of operation of all DER in the Hybrid Vessel

6.1.3. Test 3 - Extreme Load Demand Scenario

This section deals with an observation that was made with an extremely chaotic load profile that was recorded to be a relatively rare event. However the load demand consistently fluctuated within a few minutes, as result of which the operation of both DGs was similar to that of a peak demand generator.

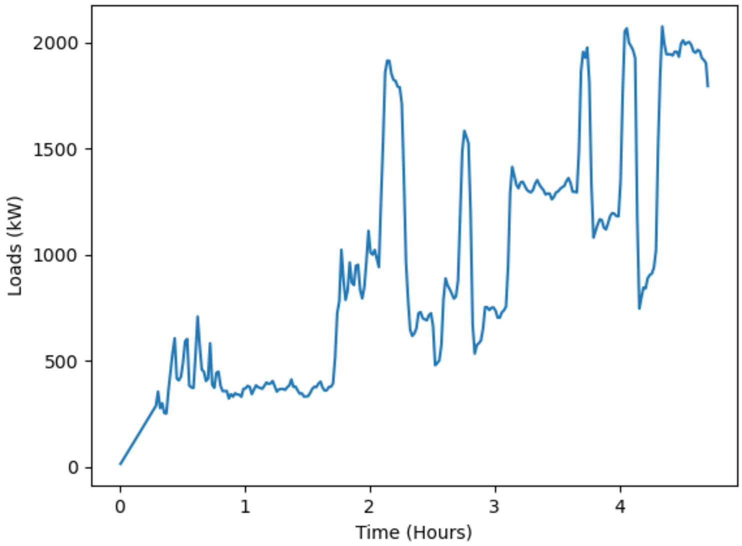


Figure 6.18: The load profile of of extremely chaotic oceans

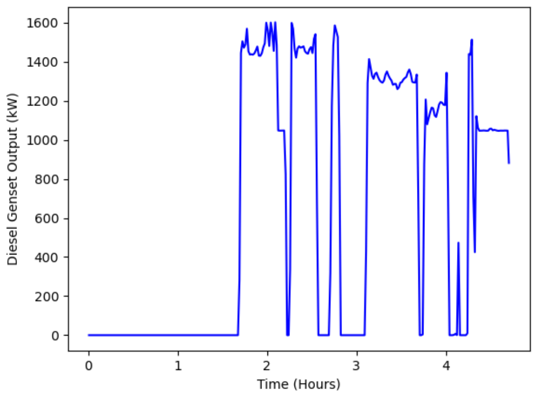


Figure 6.19: DG1 under optimized EMS Control

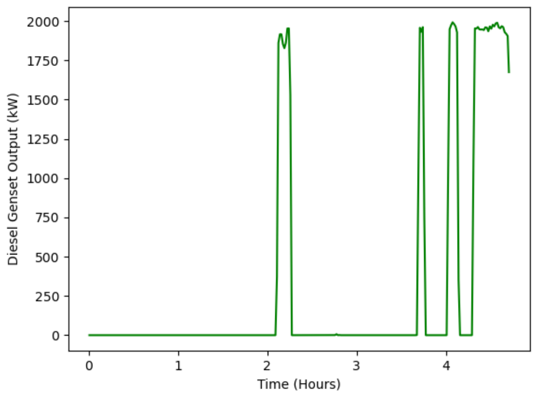


Figure 6.20: DG2 under optimized EMS control

As indicated by figures 6.19 and 6.20, both the DGs did operate at high loading points suited to their rated capacities. However, this was at the expense of the operating for a short period and then having to return to standby mode. Furthermore, it can be seen on Figure 6.21 and Figure 6.22 that for the same load profile, the vessel operator maintained synchronous control of the DGs. Whilst the DGs have not operated at their most optimum loading point, here they do not exhibit the characteristic of intermittent operation. The main limitation of the existing EMS algorithm is lack of knowledge or predictability of future loading events. Therefore, the EMS at times cannot make the best decision for long term operation of DGs in such loading scenarios.

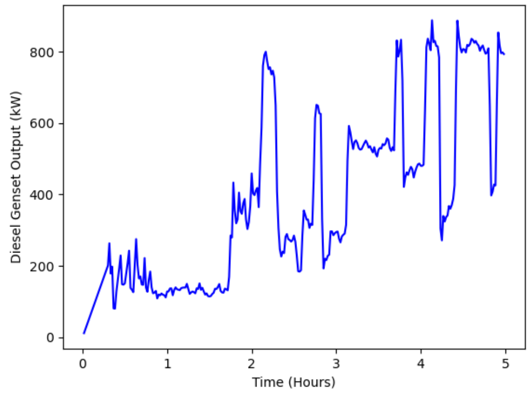


Figure 6.21: DG1 under Vessel Operator's Control

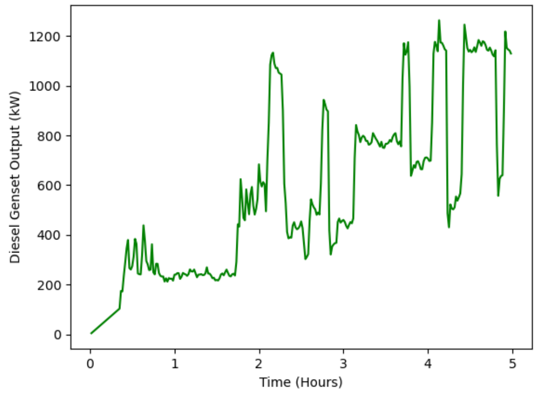


Figure 6.22: DG2 under Vessel Operator's Control

Therefore, the requirement of human intelligence to take over and operate the system in such high loads, in short intervals is seen as necessary. This is to reduce risk, and the undesired short term operation of DGs. It is therefore assumed that the vessel operator has sufficient access to data and information regarding sea conditions, temperature, wind speeds in order to make an approximate estimation of this probability. To overcome this issue, it was decided to add another feature to disable the EMS. This would then enable the vessel operator to take over control.

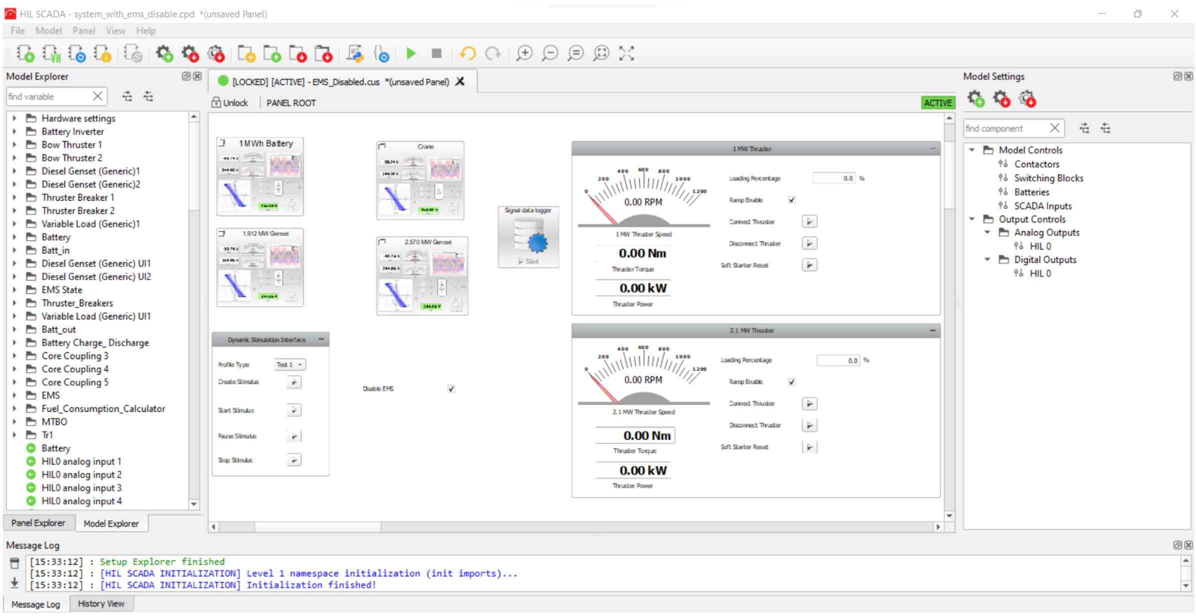


Figure 6.23: EMS Disable Mode

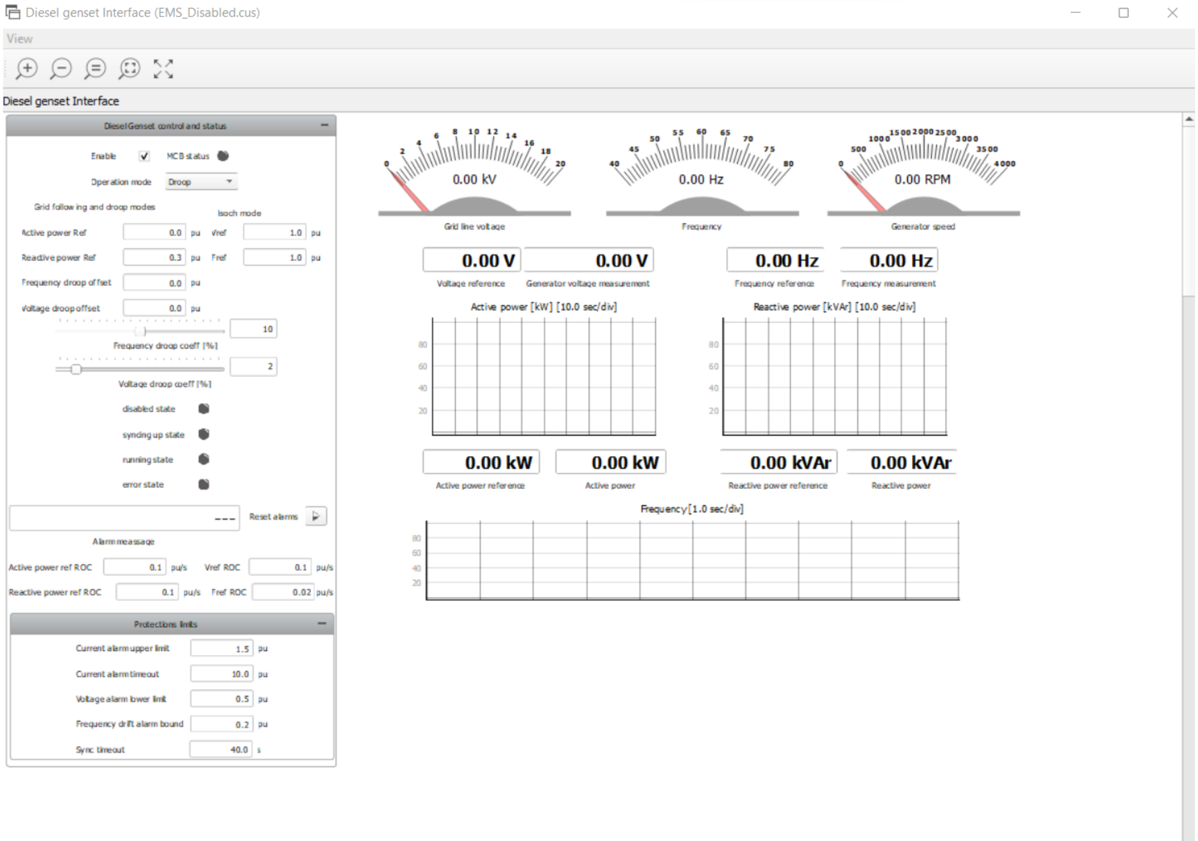


Figure 6.24: DG Control Over to Vessel Operator

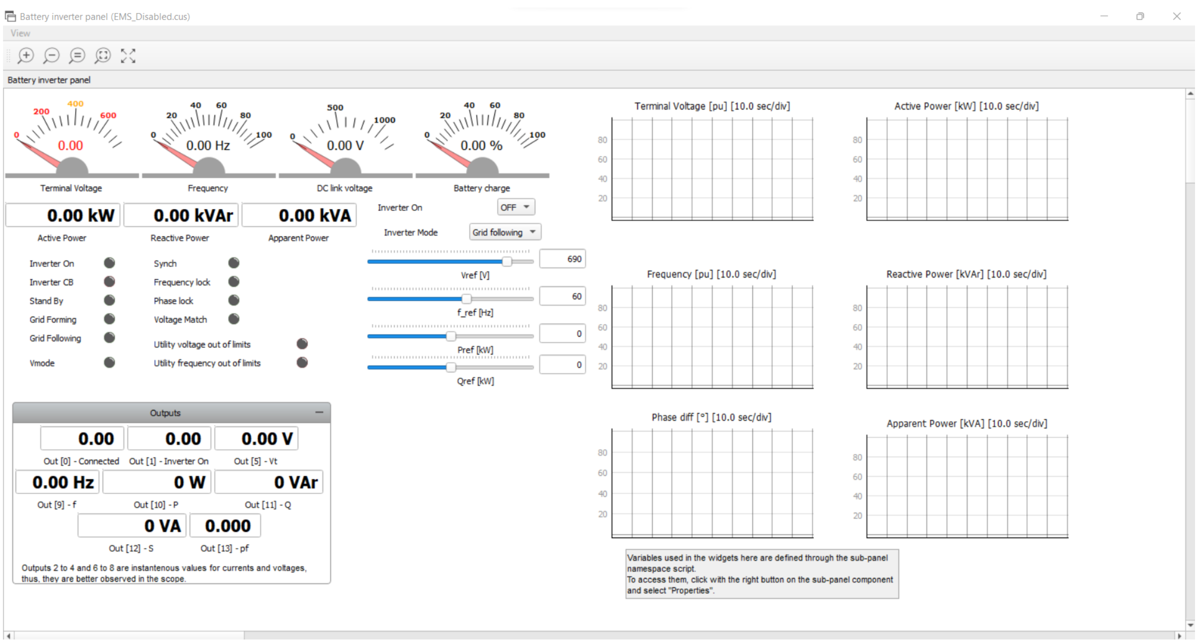


Figure 6.25: Battery Control Over to Vessel Operator

This chapter dealt with the long duration test results for the average scenario, the long duration scenario and extreme case scenario. The final results and conclusions are discusses in chapter 7.

7 Results and Discussions

This chapter discusses the potential fuel savings, DG maintenance savings, carbon emission reduction and feasibility of the proposed hybrid vessel. The main focus of these results will be around the most probable load demand scenario from chapter 6. Answers to the original research questions, and scope for future work and development are also discussed.

7.1. Most Probable Load Demand Scenario Analysis

As observed in the previous chapter 6, figures 6.4 and 6.7 indicate the change in the existing load profile. The additional load delivered by the DG to charge the BESS alongside the load demand has guaranteed the operation of the DG in a high efficiency region. However, there are two important points to be noted:

- The DG is delivering more energy.
- It is providing more energy for lesser extra fuel consumption, but the extra energy delivery is also consuming some fuel.

Therefore, in the absence of any additional power source that consumes little or no fuel, fuel saved at the end of a cycle will be on the lower side. The vessel has no other energy providers such as solar panels, wind turbines or regenerative brake energy from the crane that provides energy for free. The DGs will need to support the BESS, during the charge phase. The specific fuel oil consumption between 60% and 80% changes at the rate of the third decimal. So, the fuel saved will be small with every additional kWh delivered. Hence comparing the fuel consumption between the hybrid vessel and non-hybrid vessel is not a fair comparison.

The comparison is to be made between the use of optimized EMS, and existing EMS control in the DP2 mode of the same hybrid vessel. For this purpose, one assumption that has been made is that with the existing EMS, synchronous control is used. Thus the 1000kW of power to charge the BESS is shared equally between both the DGs. Therefore, the new profiles of operation in synchronous control of the DGs and BESS is required. This profile has been simulated to mimic the the exact operational limits for the BESS DoD as set by the optimized DG control with the new EMS.

Figures 7.1 and 7.2 indicate the new operational profile of the hybrid vessel when operated under synchronous control. As seen on these figures, this operation of the vessel under synchronous control is kept as close as possible to that of optimized EMS control for comparison later in this chapter. Here too, the BESS cycles thrice and does not discharge towards the very end of the cycle, in order to mirror the BESS operation under optimized EMS control. It is to be noted that the charge phase of the BESS is much faster in synchronous control, as 1000kW is continuously guaranteed. This implies that the BESS would be available more often for discharge. Therefore, it is possible that the net fuel consumption in this operation is much lower, however it comes at the expense of additional cycles of the BESS. Extra cycles of the BESS are costlier than current fuel costs in the market. Another challenge the synchronous control of the DGs experience, is the average loading factors of both DGs still remain below 30%. The additional few liters of fuel saved will not make up for the cost of maintenance for the

DGs due to wet-stacking events. At this low loading factor, the probability of incomplete combustion is higher. Whereas in the optimized DG control, any excess power available after meeting the load demand is used to charge the BESS. The speed of charging will be slow, dependent on load demands at the time. The optimized EMS control results in an average loading factor of about 73.4% throughout the operation. This approach prevents the susceptibility of the DGs to wet-stacking, which implies maintenance cost savings. Finally, at this high load factor, the probability of incomplete combustion is greatly reduced, thereby reducing carbon emissions, that will be subject to the EU ETS. Hence the optimized EMS control has better monetary benefits in the long-term.

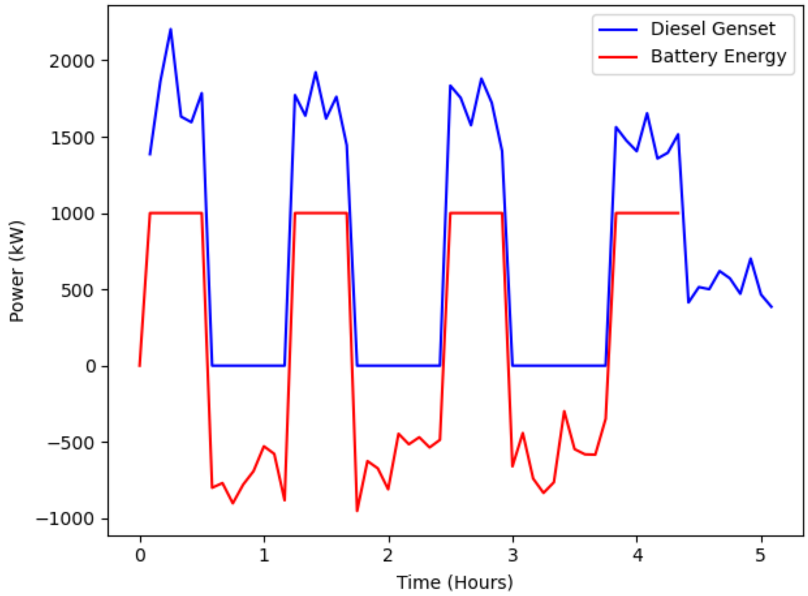


Figure 7.1: Operational Profile of the Vessel Under Synchronous Control

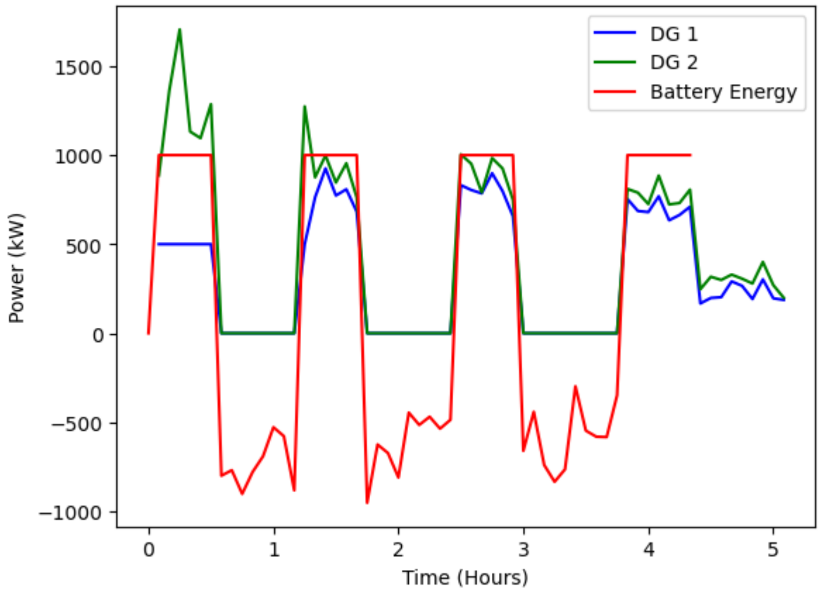


Figure 7.2: Overview of DER with Synchronous Control of DGs

After conducting simulations in Real Time on Typhoon HIL with an optimized EMS and non-optimized

EMS control (Synchronous Control of DGs), the following observations were made. The fuel consumption from the optimized EMS control at the end of the 5 hour cycle is found to be **908.65L**. Whereas the fuel consumed at the end of 6 hour cycle under synchronous control of the DGs is found to be **966.39L**. **Therefore the reduced fuel consumption from the optimized control of DGs for this hybrid vessel comes up to 5.98%**. It must be noted that the fuel savings with the optimized EMS control can be higher, had the DGs been completely shutdown. Due to redundancy requirements in the DP2 mode, and the EMS limiting discharge of the BESS to 1C, the DGs must be kept on standby. This results in a standby mode fuel consumption, during the BESS operation. Although this fuel is not going towards meeting energy demands, it is a necessary consumption, to ensure sudden large demands are met as per DP2 requirements.

Table 7.1: Comparison between Optimized EMS Controlled DGs and Synchronous Control of DGs for the Average Load Demand Scenario of the Hybrid Vessel

Parameter	Optimized EMS	Synchronous Control of DGs
Net Fuel Consumption in Cycle	908.65 L	966.39 L
DG1 Average Loading Range	73.4%	29.51%
DG2 Average Loading Range	Standby Mode	30%
DG1 MTBO (years)	1.71	1.29
DG2 MTBO (years)	Standby Mode	1.29
DG1 Expected Maintenance Cost (per year)	€ 50,904	€ 67,084
DG2 Expected Maintenance Cost (per year)	Standby Mode	€ 67,084

The comparison between use of optimized EMS control and synchronous control of the hybrid vessel is illustrated by Table 7.1. **Clearly, it indicates that the vessel can be operated with greater performance and efficiency under the optimized EMS control approach**. The optimized EMS control ensures loading of DGs above 70% on average, an average fuel consumption reduction of 5.98%, maintenance cost savings and additional operational hours for the DGs by delaying the MTBO. Furthermore, with the additional available operational hours of the DGs, the vessel owner benefits with more business hours. The monetary gains that can be achieved from this is unknown to the author at this time. However, this is an additional incentive the vessel owner has to gain from delaying the MTBO.

Table 7.2: Estimates from Non-Hybrid Vessel Configuration

Parameter	Non - Hybrid Vessel
Net Fuel Consumption in Cycle	918.769 L
DG1 Average Loading Range	13.45 %
DG2 Average Loading Range	16.95 %
DG1 MTBO (years)	0.7
DG2 MTBO (years)	0.7
DG1 Expected Maintenance Cost	€ 108,173
DG2 Expected Maintenance Cost	€ 108,173

Table 7.2 provides an overview of how the existing vessel fared in the same load profile. The key takeaways to be noted from this information is that the DGs provide much less power for a significant amount of fuel. Moreover, on average DG1 loaded at 13.45% and DG2 at 16.95%. Therefore, at such low average loading factors, the maximum number of operational hours the DGs can provide before having to go into long overhaul is shorter. This operation of the DGs makes them susceptible to wet-stacking events, thereby significantly raising the estimated maintenance costs of the diesel generators.

7.1.1. Fuel Cost Savings and Maintenance Cost Savings

For this analysis, it is assumed the vessel operates for a total of 10 hours each day for 80% of the year. Therefore the following calculations were derived. Table 7.3 indicates the annual savings to be expected from the implemented hybrid vessel along with the optimized EMS control. With the EMS control optimizing the DGs and use of BESS, an estimated 58 tons of MGO can be saved per year.

Additionally, nearly € 50,000 can be saved in maintenance and overhaul savings per DG per year, due to the high average loading factor. This number was also vetted by the vessel owner. On average the saved cost of DG1 maintenance comes to € 57,268 while for DG2 it comes to € 68,173. This is because of an assumption that the cost of maintenance of DG2 will be lower, due to lower overall operation. On average, a total of € 291,579 can be achieved in savings for this vessel, subject to changes in the fuel market. As of July 15th 2024, the price of MGO at Rotterdam Bunker was recorded at $ 758.5/ton MGO [41]. The currency conversion rate from United States Dollar (USD or $) to Euros (EUR or €) as of July 15th 2024, is at 1 USD = 0.92 EUR [42].

Table 7.3: Net Savings per year

Parameter	Value
Net Fuel Savings on PS and SB	67,448.496 L
Net MGO Saved on PS and SB	58,005.71 kg
Average MGO Fuel price	758.5 $/ton
Fuel Cost Saving	€ 40,697.53
DG1 Expected Maintenance Savings	€ 57,268.10
DG2 Expected Maintenance Savings	€ 68,173.08
Net Fuel and Maintenance Savings on PS and SB	€ 291,579.88

7.1.2. Emissions Offset

With the EU ETS coming into place, there is the added interest for vessel owners to limit their GHG emissions. The emission factor for Marine Gas Oil from Tank to Wake is estimated to approximately 3.206 tons CO_2 per ton of MGO [43]. The net emissions saved from reduced fuel consumption, amounts to a total of **185.96 tons of CO_2 annually**. It is also important to note, that now since the DGs operate at a high operating efficiency region, the process of incomplete combustion is no longer existent. Thus, the reduced emissions from this operation should be even greater. However, due to lack of a reliable source that can accurately estimate the emissions at different load factors, this calculation has been omitted.

The exact cost of the emitted pollution for the maritime sector, is yet to be determined by the European Commission. The exact cost of emissions will be decided, once the Commission has the necessary data regarding total emissions. With the Cap and Trade approach, the emission allowances they need to make available in the market will be known and by far, their prices. The ambition to make sure vessels emit only as much as their allowances allotted, will also be a consideration for the Commission [44]. The authors of [45], made a model to determine cost of emissions. The cost of offsetting CO_2 emissions for this vessel is shown by Table 7.4.

Table 7.4: Saved Money of Emission Reduction

Emission Cost €/ton CO_2	€ 30/ ton CO_2	€ 67/ ton CO_2	€ 150/ ton CO_2
Saved Costs Annually (€)	5,578.92	12,459.58	27,894.6

7.1.3. Capital Investment into Hybrid Solution

The investment into the BESS technology for the Port Side and Starboard side, for high energy batteries, power converters and filters were retrieved from two major corporations. They had similar quotes. They are indicated by table 7.5. A total of € 1,928,572 is the expected cost of investment into the modification of the vessel.

Table 7.5: BESS & Power Converter Investment

Component	Units	Cost per Unit (€)	Net Cost (€)
BESS	2	714,286	1,428,572
Power Converters and Filters	2	250,000	500,000
Total Expense			**1,928,572**

7.1.4. Simple Payback Time

Table 7.6: Simple Payback Time of Investment

Fuel Price	Average Scenario	700 (€/ton)	800 (€/ton)	900 (€/ton)
Annual Fuel Cost, Maintenance & Emissions Savings	€ 304,039	€ 303,946	€ 309,746	€ 315,547
Simple Payback Time (Years)	6.34	6.34	6.22	6.11

The Simple Payback Time (SPBT) is a measure of how long it takes for an investment to pay for itself. In the average scenario calculation, the price of fuel is taken at $ 758.5/ ton MGO. The emission allowance price of € 67/ ton CO_2 is considered for all fuel price scenarios, as their price is yet to be determined by the EC. Table 7.6 indicates the expected SPBT for the investment into the Hybrid Vessel Solution. The SPBT varies between 6.11 years and 6.34 years subject to price changes in the fuel market and ETS Emission allowance market. Clearly the cost of Marine Gas Oil in the market is currently not high enough to see substantial savings, with every additional percent of fuel saved. Most of the savings will need to be derived from the overhaul maintenance costs. Finally, with the assumption the the BESS will operate for at-least 10 years, the return on investment (ROI) for the remaining 3 years would come up to € 912,117.

7.1.5. Potential Options to Shorten Simple Payback Time

In theory, there are some alternative approaches that can be taken to reduce the simple payback time. They are listed below.

1. If the BESS can be sized sufficiently large enough to meet load demands up to 2.5 MW for 15 minutes, then DG2 can fully switch off. The result of this situation is that there would no longer be any standby fuel consumption. This can save several tons of MGO each year.
2. In the Auto and Sailing Modes, there is increased opportunity to fully shut off DGs. This is because class requirements do not state this operation to be critical. Therefore, with 2 or more DGs fully shutdown, the most optimum DGs operate, reducing fuel consumption and maintenance costs. This can save several tons of MGO each year and reduce GHG emissions with improved combustion efficiency. Finally, the maintenance savings can also be expected to be on the higher end, due to optimal loading of the DGs.
3. The improved combustion efficiency, due to high load factor implies lesser emissions per ton of MGO used. At the time of this research, there was no access to reliable data that could state the emissions at high and low load factors, to calculate the saved emissions. Nevertheless, at high load factors and improved combustion, the savings from EU ETS can be significant. This will become more and more important as the EC reduces the available emission permits, as the vessels transition to cleaner technologies.

Upon obtaining reliable data from the manufacturer regarding emissions and simulations on other operational modes, the savings estimate can increase. This will guarantee the shortening of the Simple Payback Time, to the range of 5 to 6 years or shorter. This is especially important to make this solution commercially viable and encourage other marine operators to decarbonize their vessels.

7.2. Answers to Research Questions

The objective of this thesis was to determine the best possible EMS control for the proposed marine hybrid. How the EMS achieves optimal DG operation, maintenance cost reduction, and fuel and emission reduction will be discussed below. Finally, the economic profitability of the designed configuration is described.

Sub Question 1: How can the EMS of the proposed hybrid configuration of the vessel, optimize the use of their energy sources?

The DP2 operation mode is a critical operation mode of the marine vessel. The redundancy requirements stipulate the need for continued operation, even in the event of failure of any component. The BESS provides additional energy and enhances the resilience of the electrical grid. Based on the load data and designed control structure for the EMS, it was possible to operate the vessel with DG1 in combination with the BESS. DG2 can be placed on standby, instead of operation at low loading points. This observation was made for the most probable load demand scenario. The EMS maintains control, by passing all load demands below 1000 kW to the BESS. For all loads below 1000 kW, the DGs operate inefficiently. The result of inefficient operation is increased specific fuel oil consumption (L/kWh), and incomplete combustion. Incomplete combustion leads to increased GHG emissions and wet-stacking events, causing expensive maintenance costs.

Therefore, the EMS in this case, makes an informed decision, based on the load demand. It ensures that the DG, when in operation, maintains a consistently high loading value in the range of **55 % - 80%** , depending upon the load demand at the time. In this DG loading range, the specific fuel oil consumption (SFOC), is brought to a lower level (**0.22 L/kWh - 0.21 L/kWh**) from the initial consumption range (0.43 L/kWh - 0.26 L/kWh). The advantages to this operation include increased available operational hours for the DG before entering overhaul and better combustion efficiency. At this loading range, the generator is less susceptible to wet-stacking events. This means that there are monetary savings to be achieved from reduced maintenance costs, as there will be fewer components to replace. Furthermore, the improved combustion efficiency in the high loading range guarantees more energy delivery for lesser emissions. This is a critical aspect for vessel operators as the EU ETS enters into force, requiring them to optimize their DG emissions performance.

At load demands greater than 80% of the rated capacity of the DG, there is increased risk of corrosion and erosion of DG components, again leading to expensive maintenance costs. The additional increase in maintenance costs in this case, is not supplemented from reduced fuel consumption savings. This is because current market prices for Marine Gas Oil is quite low, to realize substantial monetary savings. So the EMS implements load levelling, the BESS meets any load demand exceeding the 80% capacity of the DG, as long as it is less than or equal to 400 kW. If the load exceeds this range, then DG2 enters into operation, as this load demand is in the region of high efficiency for this generator. This ensures that there are better fuel savings and fewer maintenance costs, as the DGs no longer operate in low or very high load ranges. Further details of the maintenance savings and fuel consumption can be found in chapter 3, chapter 4 and in earlier sections of this chapter. It is important to note, that the EMS is able to optimize this operation only in combination with the BESS. In conclusion, the EMS is able to improve overall fuel efficiency, reduce GHG emissions and utilize the most efficient DER, depending upon the load demand.

Sub Question 2: How do the different operational profiles of the vessel impact the EMS's ability to efficiently make use of the distributed energy sources in the network?

The different operational profiles are an important parameter to consider for the EMS's robustness in decision making. Therefore, tests were conducted based on load demands experienced by the vessel in the Taiwan Strait and North Sea, with both low and high initial battery state of charge. The EMS strictly enforces the set rule that the BESS cannot charge or discharge any energy greater than 1C. Should the load demand exceed 1000kW at any time, the DG enters into operation to meet the load demand. This also ensures that when the DGs operate, they operate at a minimum of 55 % - 60 % and maximum of 80%, of their rated capacities. From the vessel operational data from chapter 3, it can be noted that the BESS will cycle more often in Taiwan Strait region, than that of the North Sea. This is due to very different sea conditions experienced in these regions, which results in very different load demands. The Taiwan Strait region experiences lower load demands, probably due to calmer seas, which often lie in the region of low efficiency for the DG. Therefore, in this control setup, the BESS meets these load demands. Whereas in the North Sea, there can be instances of high load demand, wherein the DGs can operate in a region of high efficiency on their own. Owing to this phenomenon, the BESS cycles lesser, as the loads are met by the DG at a much better efficiency. On average with the new EMS control, the loading percentage of the DG is in the range of 70 % - 78 %, subject to changes in the vessel operation load demand. The EMS operated the vessel using the best available DG and / or BESS, depending upon the load demand at the time. This chosen loading range helped extend the minimum time before overhaul, giving more operational hours for the DG at better SFOC.

Sub Question 3: How do the EMS's decisions optimize the operation of the vessel with its constraints such as the DG maintenance, fuel consumption minimization, carbon emission reduction and BESS maintenance?

The new EMS guarantees that under normal operation, the DG will not operate at load demands less than 1C or 1000kW. This ensures that DG1 operates at a minimum of 55%, which corresponds to a high efficiency operation region. This is important to avoid the damage caused to the DGs due to wet-stacking. Continued operation in this loading point also results in a reduced SFOC at about 0.22 L/kWh. With continued increase in the DG loading, the SFOC shifts to approximately 0.21 L/kWh. From this approach, the DGs deliver much more energy for the fuel it consumes, in comparison to the fuel it consumes at lower operating efficiency regions. Effectively, the fuel consumption has been minimized. With respect to the fuel saved, the most probable load demand scenario is taken as the case for reference. A total of **5.98%** reduced fuel consumption can be achieved with the new EMS control, against the existing synchronous control for the same number of BESS cycles. Furthermore, it is worth noting that with the optimized EMS control, the average load factor of DG1 was 73.4% and DG2 was on standby. Whereas, with the synchronous control approach, the average load factors of DG1 is 29.51% and DG2 is 30% respectively. With synchronous control, the hybrid vessel is still susceptible to high maintenance costs due to low DG loading and high fuel consumption for the limited energy it delivers. At 30% average load factor, the DG is vulnerable to the effects of wet-stacking and incomplete combustion, increasing maintenance costs and GHG emissions, for the limited energy it delivers. With the optimized EMS control for the hybrid vessel, the vessel benefits from lesser fuel consumption for the energy it delivers. The optimized EMS control also ensures the DGs are less likely to suffer from wet-stacking events and thus reduce expensive maintenance procedures. With respect to the BESS maintenance, the new EMS control maintains a strict 50% DoD, to extend the useful lifetime of the BESS.

Sub Question 4: What are the projected monetary savings that can be achieved from the proposed Hybrid Vessel Solution? Can this model be profitable?

The principal question behind every investment is the profitability of the proposal. The largest profits out of this designed configuration, is derived from maintenance cost saved for overhaul. The DGs, due to operating in the region of high efficiency, now require fewer components to be replaced as part of corrective maintenance procedures. Based of numerically simulated calculations, € 250,882 can be saved for each year of continuous operation of the diesel generators. The vessel owners confirmed a nearly similar value of about € 50,000 for each DG. With respect to fuel savings, there is a limitation. Given that the DP2 mode is a critical operation mode, it requires almost instantaneous positioning response to environmental forces. There can be some instances wherein the total load demand can exceed 2500 kW in a matter of 1 to 2 minutes on each island grid. Therefore to guarantee extra resiliency, the vessel operator would at the minimum expect the DGs to remain on standby, to support the vessel. This is due to the fact that the BESSs installed are of the high energy type and the EMS does not permit them to discharge energy greater than 1000 kW. As a consequence of this, there is a standby mode fuel consumption at the rate of 10 L/ hour. This consumption reduces the fuel savings that can be achieved, when the BESS is meeting load demands. Therefore, on average for the DP2 operation in a year, a total of 58 tons of MGO can be saved, which amounts to about € 40,698 per year based on the fuel price of $ 758.5 / ton MGO. The emissions offset from the saved fuel each year amounts to about 185.96 tons a year. Whilst the European Commission (EC) is yet to set a price on emission allowance, it is assumed from reliable sources, that the commission would start at a price close to € 67/ ton of CO_2. From the emissions offset due to reduced fuel consumption, a total of € 12,459 can be saved each year.

All in all, with the EMS control and hybrid solution, the monetary savings comes up to € 304,039 each year. With the investment made into the BESS, power converters and filtering components, the Simple Payback Time can vary anywhere between 6 and 7 years. In order for the Simple Payback to become shorter, there needs to be stronger regulations implemented, to make fossil fuels and CO_2 emissions more expensive than they are right now. With an additional assumption that the BESS network would remain operational for at-least 10 years, the additional 3 years would offer a total return on investment (ROI) of about € 912,117. With BESS prices expected to decrease in the years to come, the vessel owner benefits from being able to invest in the next set of batteries, with the saved revenue. In conclusion, the proposal can be profitable for the DP2 operation mode, subject to fuel and emissions market prices. The costlier the fuel and emissions become, the shorter the simple payback time and larger the return on investment. Furthermore, with the delayed overhaul time and additional operational hours available for the DGs, the vessel owner gains from their commercial activities, which saves money that would have been lost due to more frequent maintenance breaks. The author at this time, cannot confirm the exact commercial value, the vessel owner can gain.

7.3. Future Work and Limitations of Current Work

Whilst this thesis attempts to address the potential to hybridize and decarbonize the maritime sector, there is the scope for further development and improvement. There were some limitations experienced with the use of Typhoon HIL, as a result of which, some tests had to be omitted. There are limitations to the control logic design, such as BESS degradation, which had to be ignored, to keep within the scope of this research. The EMS's ability to predict future load events is another limitation, which can be addressed with new solutions. They are discussed in the upcoming sections.

7.3.1. Future Work

From chapter 4, the challenges with the use of the Typhoon HIL device have been noted. Additionally, this section describes some potential design approaches, that can be considered for further development of this thesis work.

1. Address and solve instability problems that arise with the core couplings. There needs to be a detailed understanding as to why issues with model stability have occurred. There are multiple parameters alongside the core coupling that can influence model stability. For example, the additional series impedance for the DG generic component. The permutations and combinations for model stability now increase with each additional generator, thruster or BESS component on the grid.
2. The existing control logic only ensures the BESS operates within 1C during charge and discharge. However, the EMS cannot make decisions to limit the cycles the BESS makes. Therefore, future work can be towards bettering the EMS for BESS cycling optimization.
3. How can the voltage drop caused by the inductive elements, in the core coupling be avoided? Due to the voltage drop created, high loading of thrusters DGs above 90% of their rated capacities, have resulted in instability problems.
4. From estimated calculations, it is expected, that greater fuel savings can be achieved in the Auto and Sailing modes of the vessel, please refer Table 3.3 for information about these modes. However, it was not possible to simulate and verify the same, due the challenges with the core couplings.

5. With the availability of the entire vessel and busbar connections between the Port Side and Starboard Side, the EMS control logic will need to be further developed to optimize the Auto and Sailing mode fuel savings and DG maintenance schedules.
6. Discuss with the Typhoon HIL engineering team, to understand how global optimization solutions, built on Python, can be implemented to the available HIL setup. Whilst global optimization solutions can provide the best solution to the specific problem, their implementation in the real time simulation environment remains limited. This is again attributed to the large computing and memory demands, these algorithms can have.
7. Transfer designed control logic to designated micro-controllers and test them on the additional available hardware test setup. This guarantees extra redundancy for the product development process. Upon verification, the controller is implemented in the actual vessel.
8. Future studies can also include exploring if increasing the BESS size, can have better monetary savings in the long run. If the BESS size is increased sufficiently large enough, to guarantee a full shutdown of the standby generator, there is no more standby fuel consumption. There is also the added benefit of shorter operating hours, that can potentially add to maintenance savings. It would be worth investigating the profitability of this configuration in the future. The profitability, design and implementation constraints will need to be thoroughly investigated.
9. Another study to verify, is the application of the combination of the High Power and High Energy BESS technology. If implemented, the additional BESS costs incurred, along-with with power converters and filters must be realized within 5 operational years.
10. A comparison between different BESS chemistries such as Lithium Iron Phosphate (LFP), Lithium Titanium Oxide (LTO) and Nickel Manganese Cobalt (NMC) can be made. The differences in energy densities, C-Rate capabilities and depth of discharge can offer new insights into potential design changes. The cost of these BESS technologies with differing chemistries also vary by a large margin. So the sizing needs to be more comprehensive considering costs and BESS characteristics in order to obtain the optimal design for a specific application.

7.3.2. Limitations of this thesis work

The main limitation of this designed control system, is the inability of the EMS, to predict future load demands. This is because the DP2 mode's largest energy consumption is towards positioning of the vessel. The positioning of the vessel is dependent on the thrusters. The load demand from thrusters are dependent on sea conditions, wind speed and temperature among others. The next limitation is that the current EMS logic, does not consider the ageing factor of the BESS, which can be another avenue to address in the future.

The application of Machine Learning (ML) into predicting load demands based off these features can be a start. From there, applying ML into the control system logic, can help the system make better decisions in the future. By this approach the fuel savings, DG maintenance costs and BESS use can be optimized to a greater degree. However, it is also important to note that this will be a step by step process, as ML algorithms are dependent on large amounts of data and training, before they can start making reliable decisions.

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A
EMS Controller Control Logic Flowchart

BESS Undergoing Charging

EMS Controller Decision Making Process

BESS Available to Discharge