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Comparison of Fuel Consumption on A Hybrid Marine Power Plant with Low-Power versus High-Power Engines

Zhenying Wu

Marine Technology
Submission date: June 2017
Supervisor: Roger Skjetne, IMT

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MSC THESIS DESCRIPTION SHEET

Name of the candidate: Wu, Zhenying
Field of study: Marine engineering

Thesis title (English): Comparison of fuel consumption on a hybrid marine power plant with low-power versus high-power engines.

Background

During the last 20 years, maritime electric installations have increased in size and scope ranging from only few systems and installations to become an industry standard. The Norwegian maritime industry is having a leading role in the development of advanced technology improving safety and performance of offshore vessels. Increased demands for energy-efficient and low emission multifunctional vessels with high availability and reliability have motivated for electrically powered vessels with improved power and energy management systems (PMS/EMS). In addition, a shift towards more complex electric energy production systems with hybrid power plants using energy sources such as diesel, LNG, fuel cells, and additional energy storage devices such as battery banks, super-capacitors, and flywheels.

Combining gensets with energy storage devices has shown through e.g. start and stop techniques to have a potential for improving the operation of the genset with the result of reduced fuel consumption, emissions, wear-and-tear, and maintenance cost. In this project we will apply optimization methods to find optimal operating point for gensets under different power demands, with regards to fuel consumption and NOx emission. Three configurations for an offshore construction vessel will be explored in this study, 1) 2 Bergen 32:40V12 gensets and ESD, 2) 8 Bergen 32:40L3 gensets and ESD 3) 30 Perkins 2506C gensets and ESD.

Work description

1) Perform a background and literature review to provide information and relevant references on:
    - Components of hybrid marine power plants; power producers, electric storage devices, DC distribution, converters, breakers, etc.
    - Engines; small versus large.
    - ESDs; typical technologies, properties and characteristics, power and energy performance, and limitations/constraints.
    - ESD usage strategy (peak shaving, reverse spinning, strategic loading, etc.)
    - Relevant optimization methods (genetic algorithm, Monte Carlo, simulated annealing.).

   Write a list with abbreviations and definitions of terms, explaining relevant concepts related to the literature study and project assignment.

2) Choose a type of offshore vessel, with a certain power capacity requirement, and specify three different power plant configurations for this vessel, two with small equally-sized engines and one with large equally-sized engines, summing up to the required capacity. Present the configurations with drawings and descriptions sufficient for the reader to understand the system configurations.

3) Formulate a relevant optimization problem, where the optimization objective is to minimize the fuel consumption and NOx emission. For a given power demand, the variable is the speed and torque of each connected engine within certain constraints. For varying power demand, you may also include a variable on how many engines that should be connected at each instant of time, with minimum 2 engines connected. A typical power demand to test on, would be stepwise 20%, 40%, 60%, 80% and 100% of the installed power capacity.

4) Apply different optimization methods on the formulated problem(s) and compare the results. Discuss the resulting cost (the cost function values) associated with each loading conditions, for the three configurations.

5) Consider the start and stop strategy and discuss if a penalty on emissions should be included, since starting and stopping induces transients and extra emissions and fuel consumption (and wear and tear) from an engine, especially for the large marine engines.

6) Compare the optimization results for the two different configurations (small engines vs. large engines) and discuss how different ESD usage strategy could influence the two configurations.

Tentatively:

7) Include the effect of efficiency degrading[1] on the fuel consumption and optimize 2) further, based on a "benchmark" varying load profile for the vessel.

8) Develop and apply a method to control the power transient within certain range so the FOC caused by transient could be reduced by the ESDs.

Specifications

The scope of work may prove to be larger than initially anticipated. By the approval from the supervisor, described topics may be deleted or reduced in extent without consequences with regard to grading.

The candidate shall present personal contribution to the resolution of problems within the scope of work. Theories and conclusions should be based on mathematical derivations and logic reasoning identifying the various steps in the deduction.

The report shall be organized in a logical structure to give a clear exposition of background, results, assessments, and conclusions. The text should be brief and to the point, with a clear language. Rigorous mathematical deductions and illustrating figures are preferred over lengthy textual descriptions. The report shall have font size 11 pts. It shall be written in English (preferably US) and contain the following elements: Title page, abstract, acknowledgements, thesis specification, list of symbols and acronyms, table of contents, introduction with objective, background, and scope and delimitations, main body with problem formulations, derivations/developments and results, conclusions with recommendations for further work, references, and optional appendices. All figures, tables, and equations shall be numerated. The original contribution of the candidate and material taken from other sources shall be clearly identified. Work from other sources shall be properly acknowledged using quotations and a Harvard citation style (e.g. *natbib* Latex package). The work is expected to be conducted in an honest and ethical manner, without any sort of plagiarism and misconduct. Such practice is taken very seriously by the university and will have consequences. NTNU can use the results freely in research and teaching by proper referencing, unless otherwise agreed upon.

The thesis shall be submitted with a printed and electronic copy to the main supervisor, with the printed copy signed by the candidate. The final revised version of this thesis description must be included. The report must be submitted according to NTNU procedures. Computer code, pictures, videos, data series, and a PDF version of the report shall be included electronically with all submitted versions.

Start date: 11 January, 2017 **Due date:** 11 July, 2017

Supervisor: Roger Skjetne
Co-advisor(s): Nicolas Lefebvre, Michel Miyazaki, Torstein Bø.

Trondheim,

Roger Skjetne
Supervisor

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[1] Power train efficiency degrading when genset runs at low load.

Summary

Due to operation cost and environmental concerns, there is ongoing effort to reduce the fuel consumption and emissions in all transportation sectors including marine transportation. In the last decade, the development of diesel electric propulsion system have made it possible to be installed on many offshore installation vessels. Electric propulsion installation becomes a prevailing trend mainly due to increased demands for energy-efficient and low emission vessels with high availability and reliability. Combining Gensets with Energy Storage Devices (ESD) has shown through different usage strategies to have a potential for improving the fuel economy as well as enhancing the genset dynamics which reduces fuel consumption, emissions, wear and tear, and maintenance cost.

This thesis has presented optimization methods to find optimal operating point for gensets under different power demands, with regard to fuel consumption and NOx emission. Three power system configurations for an offshore construction vessel will be explored in this study, 1) marine power plant with large gensets, 2)marine power plant with small gensets which has the same cylinder characteristic with 1), and 3) marine power plant with small gensets which has different cylinder characteristic with 1) and 2).

Optimization simulations were accomplished in Matlab. A typical power demand step-wise from 10% to 100% MCR has been tested in all configurations, and results have illustrated good fuel economy in configuration 2 over configuration 1. Fuel consumption was also high in configuration 3, however, it was caused by its higher optimum specific fuel consumption feature. Monte Carlo method was applied to test the sensitivity of cost function with slightly varying optimum engine operating points for one case, where it gave consistent fuel consumption and has shown the validity of optimization results. Considering AC/DC converter efficiency degrades especially at low load percentage, a study has shown that fuel efficiency is even better in configuration 2 than one in configuration 1.

Multi-objective simulations on configuration 2 was presented with 3 different load condition, 20%, 45% and 70%. It illustrates different shape of pareto front, which is a group of non-dominating optimums. Generally, it showed that in order to reduce the NOx emission, fuel consumption is required to be compromised. Due to the limitation of accessible specific NOx map, limited case study was accomplished. However, the same optimization method can apply to these maps when it is accessible.

Besides, results have indicated by integrating ESD led to fuel consumption by 5.9%, 4.8% and 6.7% in configuration 1, 2 and 3 respectively. Furthermore, configuration 1 has shown a lower fuel consumption by 6.5% and 12.7% before using ESD, and 4.9%, while 10.9% after integrating ESD during a certain operational profile. The fuel saving potential was proved to be larger in low-power engine configuration for an assumed offshore construction vessel. The performance of the proposed technique was validated through simulation results, and its advantages were demonstrated.

Aknowledgement

This work of thesis was based on the study during the spring semester of 2017 at Department of Marine Technology, NTNU. This thesis is focused on applying optimization methods to find optimal operating point for gensets in hybrid marine power plants, with regard to fuel consumption and NOx emission. Comparison study has also been carried out for power system configurations with low-power and configuration with high-power engines.
This project have been conducted under the supervision of Professor Roger Skjetne, Postdoctoral researcher Nicolas Lefebvre, PhD candidate Michel Miyazaki and Laxaminarayan Thorat, all from Department of Marine Technology.

I would like to thank Professor Roger Skjetne for introducing me to marine electrical systems and guiding me through the thesis. To Postdoctoral researcher Nicolas Lefebvre, I would like to give thanks for inspiring discussions and giving me insight in optimization methods and engine technologies. Thanks are given to PhD candidate Michel Miyazaki and Laxaminarayan Thorat for discussions of great value and inspirations. I also wish to particularly thank Michel for proof reading the thesis and valuable feedback.

My special thanks go to my friends at Department of Marine Technology at NTNU for valuable discussions and enjoyable friendship. We had memorable social gatherings and many trips which makes my time in Norway. My deepest sense of gratitude goes to my parents and my brother whose support and love is the most wonderful feeling I have ever experienced.

Zhenying Wu
Trondheim, Norway.
Sunday 11th June, 2017

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Glossary

ESD Energy Storage Devices, it stores energy and is able to consume and deliver power on demand. It includes battery, super-capacitor, flywheel etc.

Genset A pair of diesel engines and generator is called a genset.

Marine hybrid power plant A marine power system which contains at least two different power sources, such as a gas engine and a diesel engine. In this report, it is limited to a hybrid power plant which consists of a genset and an ESD .

MCR Maximum Continuous Rating, the maximum output that an electric power generating station is capable of producing continuously under normal conditions.

Acronyms

AC Alternating Current.

DC Direct Current.

DP Dynamic Positioning.

ECA Emission Control Areas.

ESD Energy Storage Devices.

FC Fuel Consumption.

GA Genetic Algorithm.

.

ROV Remotely Operated Vehicles.

SFC Specific Fuel Consumption.

Chapter 1

Introduction

This chapter will give the general introduction and description about this thesis, and the structure will be presented in the end of this chapter.

1.1 Background and motivation

In the last decade, diesel electric propulsion system have been installed on many vessels such as supply vessels, drilling ships, ice-breakers, and other offshore installations. Instead of using diesel engine to directly drive the propulsion system, the engine is first connected to a generator which produces electric power which drives the electric motors. Electric propulsion installation becomes a prevailing trend mainly due to increased demands for energy-efficient and low emission vessels with high availability and reliability. Instead of having only a few prime movers, a vessel with diesel electric propulsion often has between 2 and 10 pairs of diesel engines and generators. Gensets can be started and stopped as required in a configuration where there are more than two gensets, while at the same time keeping redundancy.

Due to operation cost and environmental concerns, there is ongoing effort to reduce the fuel consumption and emissions in all transportation sectors including marine transportation. It is usually desired to operate the engine at loading rate between 60% and 80% to achieve low fuel consumption. However, operation condition can vary a lot so that engine is not always operated within such load range. Configuring power system with low-power marine engine sets is beneficial when there exists varying load range, due to the fact that higher loading percentage per engine can be achieved by shutting down unnecessary ones. Besides, combining Gensets with ESD has shown through different usage strategies to have a potential for improving the fuel economy as well as enhancing the genset dynamics which reduces fuel consumption, emissions, wear and tear, and maintenance cost.

There are many benefits to install a modern hybrid diesel electric propulsion system with energy storage capacity instead of a traditional diesel mechanic system. Even if the investment cost is higher for a diesel electric system, it will pay off in the end as it leads to less operating cost. However, not all ships will benefit equally from this system configuration, and the advantages will to large extent be determined by the static and dynamic power requirements related to the vessel's operating profile.

Currently using ESDs in marine vessels is a new practice and it have not been long time since new rules regarding to regulating using ESDs on-board from DNV GL came out. Most vessels are designed with very well estimation of possible operation scenarios. However, it does not work well for vessels with large varying load. During operations of offshore installation vessels, there exist large range of average load from 10% to 90% and is also accompanied with fast varying load transients. With integrating ESDs in the power system, higher flexibility can be achieved.

Majority of present all-electric ships use AC distribution systems. With the development of power electronic converters in power systems, on-board DC grid has also received much attention in recent years. ABB has over the last two years run a series of project dedicated to looking at the whole on-board chain of energy conversions from a new point of view, by using DC as main distribution platform ABB (2009). There is an increasing interest in integration of energy sources and storage devices with DC outputs . The DC distribution system helps to reduce the number of conversion stages when incorporating these DC sources and devices. On the other hand, there still exists challenges with AC grid power systems, such as the need for synchronization of the gensets, reactive power flow, inrush currents of transformers and harmonic currents. The on-board DC power system enables the prime movers to operate at their optimal speeds, providing significant fuel saving in comparison to the conventional AC systems. Besides, it has also other advantages, such as space and weight savings with more flexible arrangement of equipment.

1.2 Scope

In this study we will apply optimization methods to find optimal operating point for gensets under different power demands, with regard to fuel consumption and NOx emission. Three power system configurations for an offshore construction vessel will be explored in this study, 1) marine power plant with large gensets, 2)marine power plant with small gensets which has the same cylinder characteristic with 1), and 3) marine power plant with small gensets which has different cylinder characteristic with 1) and 2).

Optimization problems will be formulated both as single objective and multi-objective problems, where the optimization objective is to minimize the fuel consumption and NOx emission. For a given power demand, the variable in the optimization problem is engine speed and torque and status (on/off) with certain constraints. Typical power demand will be tested stepwise from 10% to 100% of the installed power capacity.

GA method is to be applied to solve most of the optimization problems, while a ESD usage method proposed by Miyazaki and Sørensen (2016) has been used and compared with GA method in a case study where total fuel consumption during an operation is optimized via charging/discharging ESD optimally.

Optimization results for three different configurations are to be compared and discussed, while recommendations and conclusions should be given based on assumptions made.

The mentioned tasks and analysis mainly target designs for offshore construction vessels. Other types of vessel are not in the scope of research, due to different load profiles and power management requirements. The optimization study is based on static power requirement, while extra fuel consumption or emission caused by power transients and engine start/stop is not included. ESD usage strategies in this study are mainly start-and-stop and strategic loading, as the focus in not placed on load transients. Besides, the results from this study is very case-specified, due to the assumption of certain operational profile and load power requirement.

1.3 Contributions

The contributions of this thesis are divided in three categories of optimization formulation, fuel consumption and NOx emission analysis of a study case (an offshore construction vessel) and comparing the results from configurations with low-power versus high-power engines.

Mathematical formulations are developed for both single and multiple objective optimization studies of DC hybrid marine power system at static load. GA method has been applied to solve these problems. In order to reduce the computation burden and time while securing the optimization quality, Monte Carlo simulations are applied to optimization results for validation. Providing a load profile, two approaches to calculate fuel saving potential during an typical operation are derived based on the ESD charge/discharge rate, engine efficiency and SFC curve.

Three power plant configurations are proposed to an offshore construction vessel design, which are based on interest to compare performance of high-power engines versus low-power engines with available SFC and NOx emission map. Potential of reduction in fuel consumption have been compared among these proposed configurations in different cases considering converter efficiency degrading, intergation with ESD and a proposed typical operation.

1.4 Structure of the thesis

The structure of this thesis will be introduced here. This will help reader to catch the outline of this project report.

Chapter 2 introduces the main components in hybrid marine power plants, distribution technologies and typical ESD technologies. Different ESD usage technologies illustrate how ESD can be integrated to benefit the system.

In **Chapter 3**, Genetic Algorithm (GA) method is presented and a illustration of how GA tuning parameters affect the optimization result is included to show the how to choose proper simulation settings. In order to evaluate the resulted dataset from optimization, Monte Carlo method is introduced to show how sensitivity analysis can be achieved. Furthermore, pareto front illustrates a group of non-dominating optimization results in multi-objective optimization problems.

Chapter 4 presents the studied vessel and vessel load specification. Accordring to vessel load, three configurations are propsed which consist of different genset sizing. Single line diagram is depicted for each configuration. Formulation of optimization problem is presented for both single objective and multi-objective optimization.

Chapter 5 shows resulting fuel consumption in each configuration at typical power demands without and with considering transmission efficiency degradation. Monte Carlo simulation validates the optimization results and analyzes the sensitivity causing by varying input parameters (engine speed and torque). Integrated the configuration with ESD, the simulations illustrate how ESD usage and different strategies can influence the results from three configurations. A benchmark operational profile is assumed and fuel savings during such operation are optimized via charging and discharging ESD optimally.

Chapter 6 is the discussion and recommendation part which presents further works that could been done.

Chapter 7 is the conclusion of the whole study.

Appendix contains the SFC maps and NOx map, as well as some relevant results from multi-objective optimization.

Chapter 2

Hybrid Power Plant and Diesel-electric Propulsion

In this chapter, all relevant topics related to hybrid marine power plant, electric propulsion, ESD technology and AC/DC distribution will be introduced.

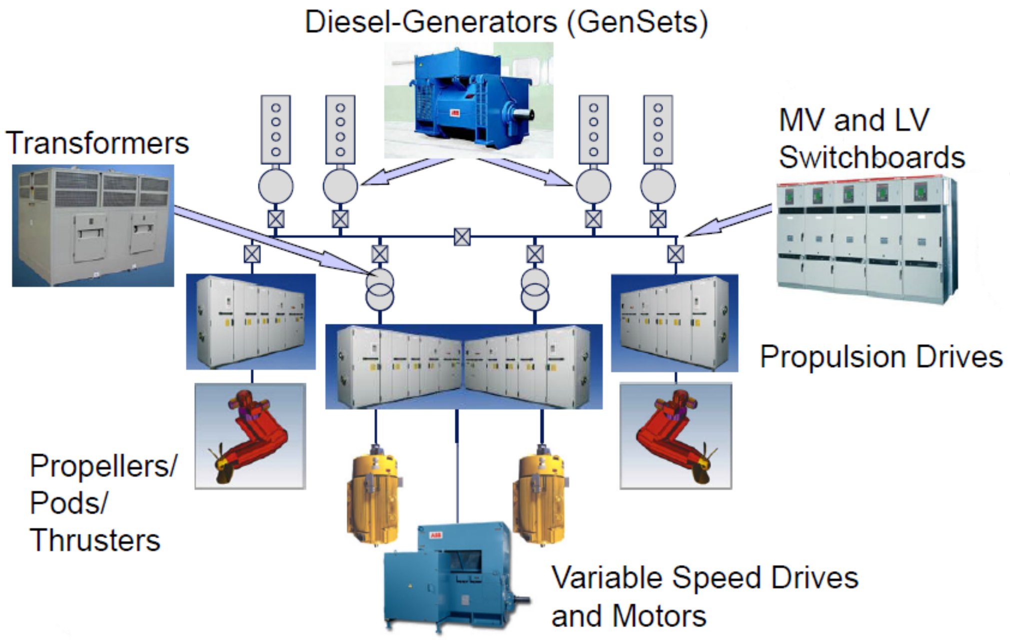


Figure 2.1: Components of electric propulsion system. Courtesy: Skjetne (2015)

2.1 Components of hybrid marine power plants

Electric propulsion with gas turbine or diesel engine driven power generation is used in many ships of various type and in a large variety of configurations. In this study, hybrid marine power plant is limited to diesel-electric propulsion with DC grid, where diesel engines and ESD are power resources.

Main components of marine electric propulsion systems are prime movers, generators, transformers, switchboards, variable speed drives and motors and thrusters/pods/propellers as shown in figure. 2.1.

2.1.1 Prime mover

Nowadays main source for electric power generation is generator set driven by marine diesel engine, or gas engine, gas turbine or steam turbine. A diesel-electric propulsion system normally has medium to high-speed engines, which is with lower weight and costs than similar rated low speed engines. It is very important to assure the availability to the power plant in all cases, therefore it is required to include a number of prime movers in a redundant network.

Combustion engines are continuously being developed for higher fuel efficiency and reduced emissions. A medium speed diesel engine has optimal SFC of less than 200 g/kWh at the optimum operation range from 60% - 80% MCR, as seen in figure 2.2.

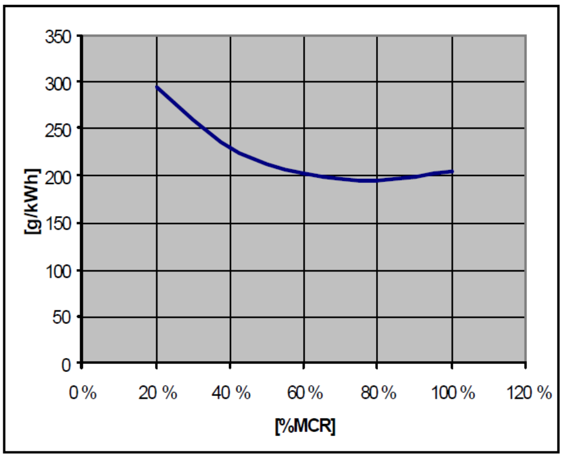


Figure 2.2: Example of specific fuel consumption for a medium speed diesel engine. Courtesy: Ådnanes (2003)

As the load drops lower than 50% of MCR, the specific fuel consumption increases fast as well as high PM, NOx and SOx emission. Therefore it is desired to operate diesel engine as close as possible to its optimum load point.

2.1.2 Generators

Generators are used to convert mechanical energy to electrical energy. Generators can be divided into induction generators and synchronous generators, the latter of which is used by majority of vessels. Synchronous generator has a magnetizing winding on rotor carrying Direct Current (DC) current, and a three-phase stator winding where the magnetic field from the rotor current induces a three-phase sinusoidal voltage when rotor is rotated by prime mover. The frequency f [Hz] of induced voltage is proportional to rotational speed n and pole number p in synchronous machine:

$$f = \frac{p}{2} \cdot \frac{n}{60} \tag{2.1}$$

Therefore, a large medium speed engine normally works at 720 RPM at 60 Hz network (10-pole generator) or 750 RPM for 50 Hz networks (8 pole generator).

2.1.3 Switchboards

The main switchboards onboard a vessel are usually distributed or split in two or more than two sections, in order to obtain the redundancy requirements of a vessel. According to rules and regulations for electric propulsion such as DP 1 and DP 2 by DNV-GL (2011), one shall tolerate the consequences of single section failure. For strictest redundancy requirement like DP 3, water and fireproof dividers must be used to segregate the different sections.

In a two-split configuration, with equally shared generator capacity and load on both sides, the worst case failure mode lead to loose 50% of generator capacity. In order to avoid a high installation costs, the system will often be split not more than four sections.

As the installed power increases, the normal load currents and the short circuit currents will increase. It is important to increase the system voltage and thereby reduce the current levels due to the physical limitations on handling the thermal and mechanical stresses in bus. NORSOK (2001) also gives the most common selected voltage levels for the main distribution system.

2.1.4 Power converter

A power converter is an electrical or electro-mechanical device for converting electrical energy. It can be a transformer, which changes the voltage of AC power according to a transformation ratio; It can also be used to convert energy from one form to another such as converting between AC and DC power.

2.1.5 Motor

The electrical motor is the most commonly used device for conversion from electrical to mechanical power and is used for electric propulsion and other on-board loads. Typically, majority of the loads in ship installations will be some electrical motors.

The electrical motors can be divided into DC motors, asynchronous motors, synchronous motors and permanent magnet synchronous motors. DC motors must be fed from a DC supply and its speed can be controlled over a wide range. Asynchronous motors is used in many applications on-board a ship due to its simple design while synchronous motors are preferred to be used in large propulsion drives (>5MW). Permanent magnet synchronous motors are used in podded propulsion applications due to its compact design.

2.2 Transmission loss

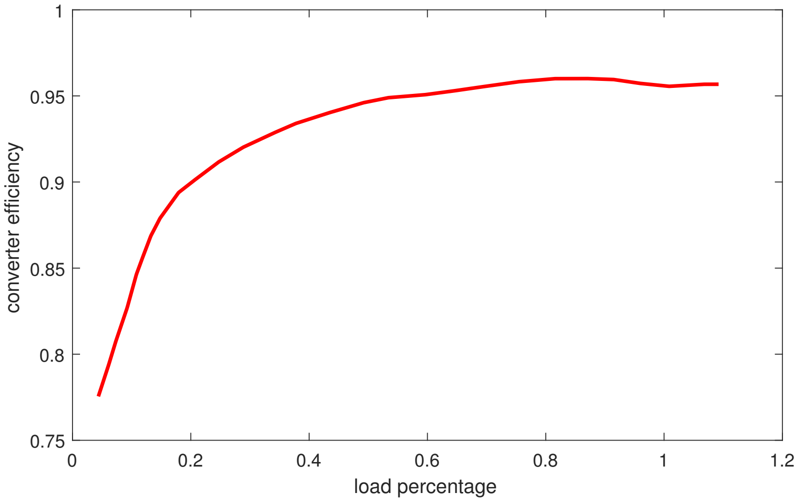


Figure 2.3: Converter efficiency against load percentage. Data resource: ElectronicDesign

From engine shaft to load, there exits transmission loss of around 10% at rated condition. The power efficiency of generator is usually considered to be around 96%, where power efficiency is defined to be its output power dividing by its input power. Power loss is typically assumed to be neglectable when it comes to switchboard, while power efficiency of power converter is assumed to be around 98%-99.5%. Meanwhile, power efficiency of electric motor is around 96%. However, all these values are specified on product's data sheet at rated condition by manufacturers. This is because many notable regulatory bodies and trade organizations have tried to establish international standards for the way in which efficiency is calculated and stated on product data sheets.

As a result, power supply efficiency is usually specified based on the operating conditions that are most favourable to the figure concerned, for example, at maximum rated load. However, for the rest of the time, it will be operating below full load, and efficiency is likely to be much lower than the headline figure. To assess the impact on heat generation within a product, one need to dig deeper into the data sheet and find the efficiency vs. load curve, if one is provided.

Figure 2.3 shows an example of converter efficiency against load percentage. Across a wide span of load range from 40% to around 100%, there exists relatively flat efficiency. However, converter efficiency degrades significantly as load percentage drops from 40% and efficiency ends up at around 77%. As we have mentioned, an offshore construction vessel encounters very large range of low load operation especially during DP, which will lead to low loading condition in the high-power engine. As a consequence, AC/DC converter load percentage in high-power engine configuration is lower than one in low-power engine configuration.

2.3 AC vs. DC distribution

Comparing a DC distribution with AC distribution, it has less components, therefore fewer efficiency losses, lighter and less space-taking. While in AC distribution system, there are more links and transformation between components. Furthermore, harmonic distortions, frequency variations are also common problem for AC distribution. Despite of this, conventional AC distribution has no problem to break the AC current mechanically. Currently, it is challenging to break DC currents due to the mechanical breaker cannot work well against the electric arc. It is vital especially as a protection against fault. Power electronics are developed for this problem and hopefully it works perfectly in the end. There is a trend to apply DC grid on board because other DC technologies such as batteries and fuel cells can easily be integrated to DC grid, which can help improving efficiency and reduce emission and wear and tear.

Most engines are designed to be operated in fixed frequency at most of its lifetime. However, developments in DC grid and frequency converter have made it possible to operate the genset in any frequency within its operational scope, given that a rectifier will transform its output into DC voltage. The ideal scenario would be with the generator running at the speed that leads to minimal fuel consumption, given any power demand.

The curves in figure 2.4 shows that by switching generators running at fixed frequency to variable frequency the fuel saving can be expected to be up 20% the original fuel consumption. It is known that the genset efficiency achieve highest performance when the load is between 70% and 80% of maximum power rating for diesel engines, as seen in figure 2.4. In many Dynamic Positioning (DP) operations, system redundancy is required. Redundancy is usually achieved by connecting more generators to the bus line than it is necessary, thus, leading to a low load scenario. At lower loads, SFC is usually lower for gensets which can operate in variable frequency than gensets operating at fixed frequency.

The obtained results have shown the benefit of operating engine at variable frequency over fixed frequency, which is one of advantages of DC grid when comparing with AC grid. However, it is also possible to operate engine at variable frequency by connecting gensets and AC grid via frequency converter.

One drawback of variable speed engine operation is that it must be assured the generator will not need to operate in a region which leads to blackout in cases with sudden load steps. Using ESD with a peak shaving strategy, which will filter high power surges, is a good way to assure that the load will not surpass the generator's operational limit.

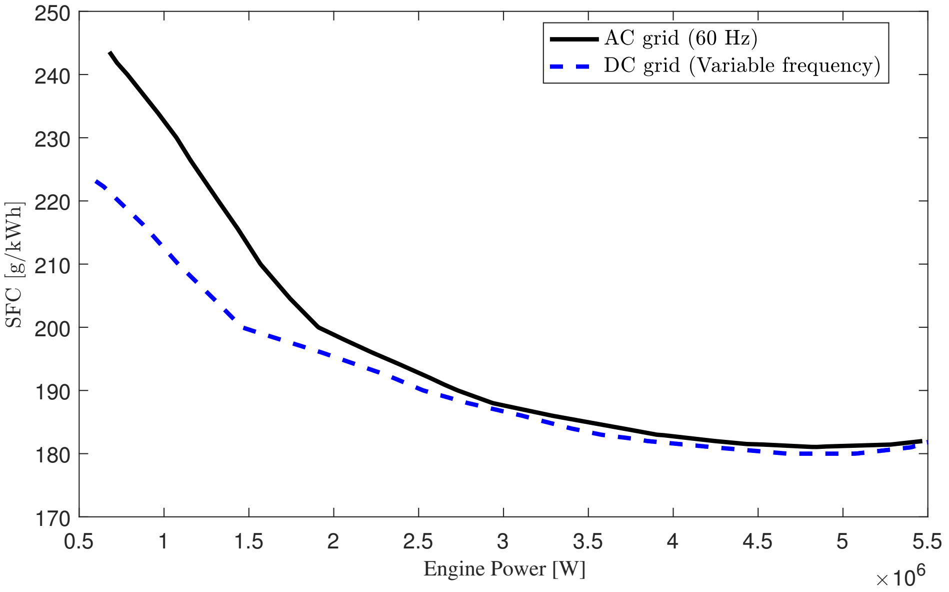


Figure 2.4: SFC comparison for a Bergen B32:40V12A diesel engine (MCR 6MW) running at fixed frequency and variable frequency.

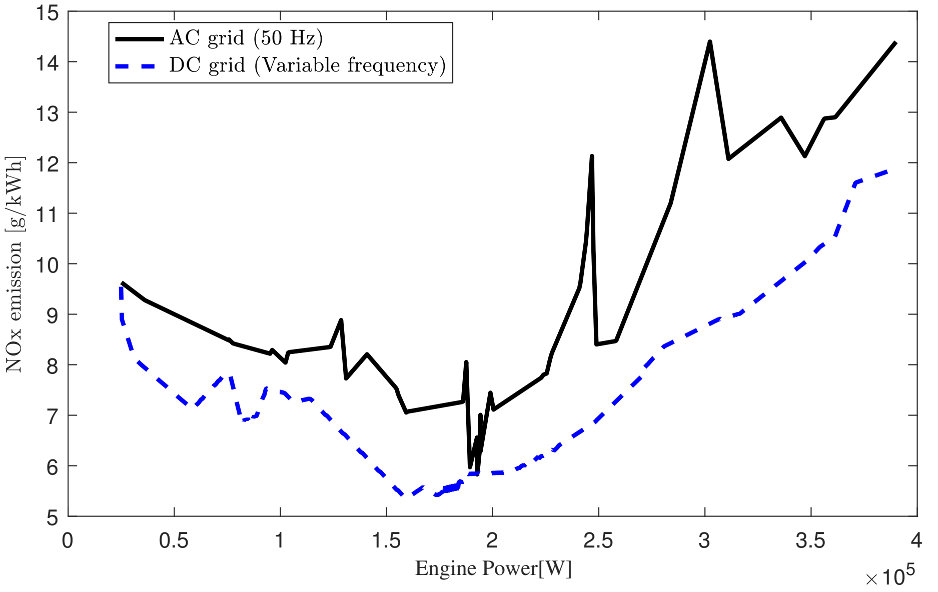


Figure 2.5: NOx emission comparison for a Perkins 2506C diesel engine (MCR 400 kW) running at fixed frequency and variable frequency.

Figure 2.5 depicts that by switching generators running at fixed frequency to variable frequency the specific NOx emission can be reduced up to approximately 40%. In practice, NOx emission can be influenced by many factors, such as intake air humidity and temperature. Besides, NOx emission is thermal product, which occurs especially at high temperatures. From the curve, specific NOx emission tends to be higher at both low load and high load, while the minimum occurs at around 40-60% MCR. Therefore, it is beneficial to to operate engine at variable speed under low and high load when it comes to reduce NOx emission.

2.4 Energy Storage Devices

ESD is energy storage device such as battery, super-capacitor, flywheel and so on. They are able to consume and also deliver power when it is at demand. It is a promising technology which allows a marine system to strategically load the genset at its optimum fuel efficiency, while keeping power production capacity.

Generally, the electrical system dynamics is is much faster than the mechanical system dynamics. It is further pointed out in Miyazaki and Sørensen (2016) that the ESD dynamics is at an order of μs. Assumptions can be made that the ESD is capable of providing the demanded power instantaneously while few fluctuations. Therefore, it is very beneficial to integrate ESD with prime movers to enhance the safety barrier of sudden load step.

2.4.1 Battery

Battery is an electro-chemical device that stores energy and then supplies it as electricity to a load circuit. Batteries are typically organized in strings and can be connected in series, in parallel, or in combination of both, to provide the required operating power.

Specifically, Li-ion batteries is considered to be promising candidate for battery bank in industry utilization. A lithium-ion battery or Li-ion battery is a type of rechargeable battery in which lithium ions move from the negative electrode to the positive electrode during discharge and back when charging. It is known as having large energy density while low maintenance. The drawbacks are the age-related degradation of battery performance and also capacity.

It is important to have a battery management system that monitors the state of charge, cell voltage, current and temperature to avoid faults within batteries. When a battery charge or discharge, it is also common to set a ramp for the battery to reach the maximum charge/discharge rate.

2.4.2 Super-capacitors

A super-capacitor is a double-layer electrochemical capacitor that can store thousands of times more energy than a common capacitor. It shares characteristics with both batteries and conventional capacitors, and has an energy density (the ratio of energy output to its weight) approaching

20% of a battery. This means that a super-capacitor could be a suitable battery replacement in situations where there is short run-time. For example, where frequent outages last for less than two minutes. In such an environment, battery deterioration is excessive due to the high frequency of the outages. This would result in a highly reliable energy storage system that would require little or no maintenance.

2.4.3 Flywheels

A flywheel is a rotating mechanical device that can be used to store rotational energy. Flywheels usually have a quite high moment of inertia and thus resist changes in rotational speed. The amount of energy stored in a flywheel is proportional to the square of its rotational speed. Energy is transferred to a flywheel by the application of a torque to it, thereby increasing its rotational speed, and hence its stored energy. Conversely, a flywheel releases stored energy by applying torque to a mechanical load, thereby decreasing the flywheel's rotational speed.

Storage of kinetic energy in rotating mechanical systems such as flywheels is attractive where very rapid absorption and release of the stored energy is critical. However, this is not the case we considered in this project and therefore focus is put on batteries and super-capacitors.

2.4.4 Comparison of ESDs

As what is shown in figure. 2.6, super-capacitor has high power density while low energy density. Therefore large super-capacitors are favored in short run-time, repetitive and power intensive applications. On the other hand, battery has high energy density while relative low power density. Thus, batteries are typically suitable for energy-intensive applications. Flywheel has a medium high power and energy density, and it is desired in the case where it can be mechanically connected to a generator directly or indirectly by a gearbox.

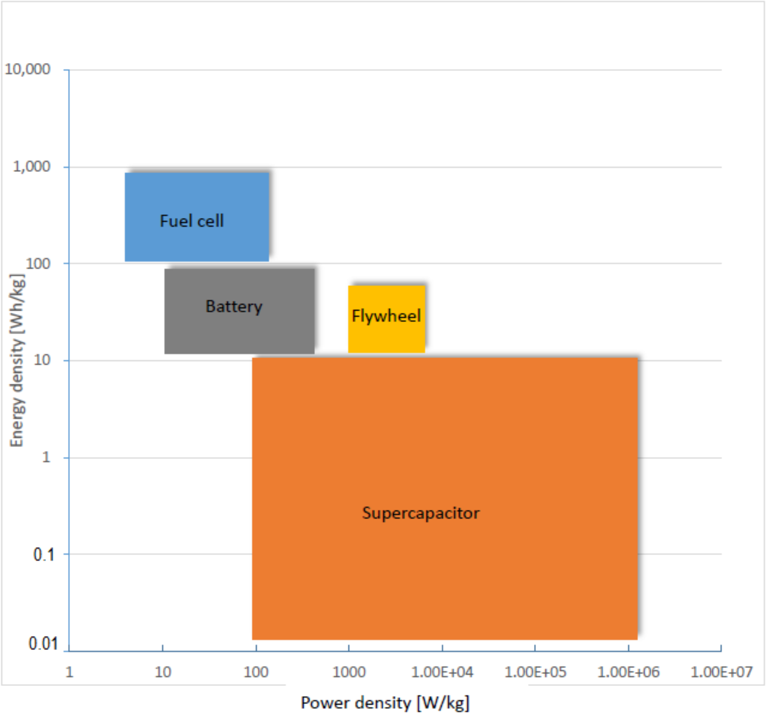


Figure 2.6: Energy storage and power handling capacity of alternative storage techniques

2.5 ESD usage strategy

One promising alternative to reduce fuel consumption and emissions is to use the newest technologies in ESD, which is device that stores energy and is able to consume and deliver power on demand.

Hybridization of ESD in marine systems has many usages, which were summed up and described in r. The most common ESD usage strategies are:

- Enhanced Dynamic Performance - It is known that it takes time for generators' loading to build up, whilst a large load step might lead to a system fault, for example a blackout, under voltage, under frequency, etc. ESD can provide energy for a system during large load steps and at the same time generator will be loaded gradually, improving the overall electrical robustness at handling load transients and sudden steps. Hence, this methodology mainly contributes to improve safety and system robustness.
- Peak Shaving - There are two approaches when it comes to peak shaving. In many applications of peak shaving, the upper and lower bound of genset deliver power is set. If the load is higher than the upper bound of genset supply power the ESD will discharge and supply the residual power. When the load is lower than the lower bound of genset supply power, the residual power from the load will be absorbed by ESD. The second peak shaving strategy is a combination of the first peak shaving strategy with enhanced dynamic performance, where

the generator-set load variation should not exceed a pre-defined magnitude. Therefore, peak shaving can lead to reduction of power transients on marine engines.

- Spinning reserve - Recent development in marine regulations such as **?** allows the usage of ESD as a spinning reserve. As an ESD can be used to ensure redundancy at dynamic positioning, less generators are needed to be connected to the bus at one point of time, which increasing the load percentage per generator and thus reducing fuel consumption and emission.
- Strategic loading - By charging and discharging the ESD, it is possible to strategically load the generator. Through high/low engine load cycles, it is possible to lower the average fuel consumption, compared to a system without the strategic loading.
- Zero Emissions Operation - By shutting down the generators and power the load only by ESD, it is possible to operate without any emission. Technology development have made it possible to supply the power demand of a vessel by a ESD with large energy capacity.

Despite usages of ESD can be categorized into these types, it is very common to combine them in pratice. For example, an ESD can be used in zero emissions operation mode at ports while peak shaving mode when there is much load transients. The general benefit of using ESD is that it allows the genset always run steadily at the optimum loading point and hence improve the fuel efficiency, emission and wear and tear.

2.6 Low-power engine versus high-power engine

Ships can have engines of all types, from 2- or 4-stroke diesel engines to turbines or even just several diesel generators that power thrusters or pods. The selection of power plant depends on what the ship is designed for and how it will be operated.

Low- and high-power engines involved in our comparison study regards mainly to engines which have same cylinder characteristics but different cylinder numbers. Due to the variations in manufacturing techniques and designs, it is hard to compare small and large engines in a wide range. Hence, low-power engines in this study refer to engines have one or several piston cylinder assembly, while high-power engines have more piston cylinder pairs.

In conventional engine design, the reasons to increase the number of cylinders are increased torque and power while improved balancing of forces and momentum. These are less important on a diesel-electric propulsion power plant design. Decreasing the number of cylinders lead to simplicity, where there are less moving parts in one engine and improved robustness, decreasing the need for service, thereby increase the availability.

Besides, turbo lag occurs and have larger affect to high-power engines than low-power engines due to the size of turbocharger, in the cases where turbochargers are installed to increase engine's efficiency. Large turbochargers take time to spool up and provide useful boost.

2.7 Genset sizing

When designing a vessel's propulsion and power system there are multiple constraints such as cost, space, weight, emission level, operational requirements, maintenance and expected energy requirements.

One issue that may have an important effect on efficiency is the power capacity (size) of the gensets. If each genset has too high capacity, the fuel efficiency will be low as load per engine will be far from optimal (60-80%). From a fuel efficiency point of view many smaller gensets are more beneficial than fewer since it will more likely run the gensets on high load. On the other hand, too many small gensets will result compromises in terms of costs, weigh and space limitations. Therefore, there might be a couple of alternatives to choose between.

On the other hand, the optimal sizing of the gensets will depend on the generation capacity requirements provided by vessel's operational profile and weather conditions in the operational area. Since it is impractical and expensive to change the gensets after the delivery of the vessel, it is essential to make a thorough analysis or estimation based on proposed power system design.

Generally, a vessel has a typical operational profile which represents what operational modes the vessel will encounter and for how long. In that case we should try to put the optimum efficiency points within these regions. It is very essential to simulate with different genset configurations based on operational profile to evaluate the different designs.

Chapter 3

Optimization Method

In this chapter, all relevant topics related to optimization method, genetic algorithm both for single objective and multi-objective optimization will be presented.

3.1 Genetic algorithm

GA is a good method to solve optimization problems. It is search and optimization method based on natural selection process that mimics biological evolution. In natural genetics, genes in the chromosomes act as a code for the physical features of each individual organism, and each organism is completely described by its gene values. The order of genes in the chromosome decide the characteristic features of individual species of a population. The different traits are passed on from one generation to the next through different biological processes such as crossover and mutation. By this process of genetic change and survival of the fittest, a population well adapted to the environment results.

Genetic algorithm consists of a population of bit strings processed by three genetic operators, which are selection, crossover and mutation. Each string represents a possible solution for the problem being optimized and each bit represents a value for a variable of the problem. Solutions are classified by an evaluation function (fitness function), giving better fitness value to better solutions. GA is an iterative algorithm applied generation by generation. In every generation, first, parents are selected depending on their performances (fitness values), and then by some genetic operators the strings of children are produced which become the members of the new population. With their calculated fitness values, the new generation is obtained in the same way. This procedure is repeated until some stopping criterion is met.

GA samples many regions simultaneously. The advantage of GA is its use of stochastic operators instead of deterministic rules to search for fitness solutions. The searching process jumps randomly from point to point, thus allowing escape from the local optimum, in which other conventional optimization algorithms might land. Therefore, GA is a very promising method to deal with complex, multi-variables optimization problem. On the other hand, the main drawback of GA is that it gives no guarantee of finding global optima.

Although GA seems to be a robust algorithm, which contains same operators and has the same evolution logic for different applications, in fact the parameter setting of GA has big impacts on the performance of the algorithm. To visualize the situation, the parameters were categorized into two groups, structural parameters and numerical parameters.

3.1.1 Structural Parameters

Structural parameters are the main factors affecting the GA performance, which include the coding scheme, operator types and stopping criterion as main parameters.

GA starts with the coding of the problem to the strings, and users should decide which genetic encoding is appropriate for the problem under consideration.

Operator selection is important because the operators are the main tools presenting the power of GA on the optimization problem. To carry the good properties of the individuals to the further generations, reproduction and crossover operators should be selected carefully. Besides, the choice of mutation type is effective on GA for not sticking on local optimums.

Another important structural parameter is stopping criterion. Different termination conditions generally lead to different performance of GA. As the evolution process requires a long period of time, GA has to be processed for a relevant duration, in order to apply its logic coming from the natural genetics. Terminating GA earlier disturbs the power of the algorithm, but the longer runs may have the inefficient use of CPU time. The most common termination condition used in GA applications is number of iterations (or generations). Large value of maximum generation number increases the CPU time drastically, while small values have the risk of improper GA performance. Hence, it is important to strike a balance between performance in best fitness value found and CPU time.

3.1.2 Numerical Parameters

Numerical parameters mainly consist of initial population, population size, maximum generation number, elitism percentage, crossover and mutation probabilities.

The population size of a genetic algorithm influences the rate of convergence and number of schemas that will be processed. Small populations may have the risk of under-covering the solution space, while large population size is not cost-effective in terms of its large computation time. If small populations are used, there may be some dominating individuals, which are always selected by the reproduction operator; thus, convergence to a local optima can occur, because search mechanism goes around the patterns of these individuals. If larger populations are used, the probability of having good individuals from different parts of solution space increases, and as a result possibility of premature convergence will decline.

Low mutation and high crossover rates bring the risk of premature convergence, while high mutation and low crossover rates decrease the GA performance in terms of carrying the better solutions to future generations. After selecting two good individuals as the potential parents, crossover rate determines whether to exchange the genetic material between the individuals or directly copy them to the next generation. Low values of crossover rate guarantees the presence of good individuals in the next generation. On the other side, this risks at losing the opportunity to recombine their good patterns, which may lead to loss of a good combination.

Mutation operator is powerful in terms of avoiding to stick to local optimums, since it gathers the diversity to the search space. If mutation occurs rarely, after several generations, similar individuals could dominate the populations, and same patterns are carried to the generations. In other words, search may occur around a local optima. On the other side, the probability of carrying the good patterns of good individuals will decrease as mutation rate increases.

GA starts with an initial population and proceeds until a termination condition is met. In many cases random populations are used as starting points. However, there are some studies (Reeves (1995)) presented the effectiveness of starting with a good population than with a random one. The initial population can be constructed from the results of some preliminary search heuristic like random search, pattern search etc. Seeding GA with good individuals speeds up the convergence to better solutions, but seeded initial population raises the risk of premature convergence. By seeding the algorithm, GA is forced to start the search around some good points (may be local optimums). If high domination of these points among the population occur, GA may converge to a local optima.

3.1.3 Examine optimization results

To search for the optimal candidates among a large number of potential alternatives within limited computation time leads to variations in the optimization results. However, it may be argued that local optima is acceptable as long as long it has good enough performance. This could be especially true regarding to engineering applications, since a local optimum may turn out to be even more beneficial than a global optimum due to practical implementation issues. For example, the performance of a global optimum deteriorates rapidly when input parameter fluctuates slightly, compared to a local optimum whose performance is not influenced by variation in input parameters.

Sensitivity is defined as the degree to which the model outputs are affected by changes in selected input parameters. By investigating the relative sensitivity of the each of the input parameters, a user can become knowledgeable about the relative importance of each of the parameters in the model. The greater the parameter sensitivity, the greater the effect of error in that parameter will have on computed results. Moreover, it is a very useful tool to evaluate if input parameter can lead to similar result despite of small changes in input parameters. Therefore, sensitivity analyses allow users to evaluate optimization results.

Doubilet et al. (1985) pointed out that Monte Carlo analysis is one of the most commonly used methods to analyze the approximate distribution of possible results on the basis of probabilistic inputs. To conduct a Monte Carlo analysis, input parameters are assigned a probability density function or statistical distribution. With the distribution and standard deviation of the probability density function based on the uncertainty associated with the parameter. Selecting the distribution is an important part of the analysis as the shape of the distribution can greatly affect the outcome. Once each input parameter has been assigned a probability density function, a computer algorithm is used to repeatedly run the model with randomly selected input values based on the defined probability density functions. Each time the model is run, the output value is saved. After all of the computer simulations are finished, the output values are analyzed and descriptive statistics and probability plots can be created to describe the likelihood of a particular outcome occurring.

In Monte Carlo analysis, the expected value $\bar{Y}$ and the variance s^2 of the output Y are estimated by the following well-known expressions:

$$\bar{Y} = \frac{1}{n}\sum_{i=1}^{n} y_i \tag{3.1}$$

$$s^2 = \frac{1}{n}\sum_{i=1}^{n}(y_i - \bar{Y})^2 \tag{3.2}$$

where n is the number of samples and y_i is the value of one simulation trial. The value of $\bar{Y}$ is not very helpful on its own, as it gives no idea how much confidence can be placed in an estimation. Variance s^2 provides an estimate of how much individuals are spread around the mean.

3.2 Multi-objective optimization using Genetic Algorithms

In real world applications, most of the optimization problems involve more than single objective to be optimized. The objectives in many of engineering problems are often conflicting, i.e., maximize performance, minimize cost, maximize reliability, etc. In the case, one extreme solution would not satisfy both objective functions and the optimal solution of one objective will not necessary be the best solution for other objectives. Therefore different solutions will produce trade-offs between different objectives and a set of solutions is required to represent the optimal solutions of all objectives.

The trade-off curve reveals that considering the extreme optimal of one objective requires a compromise in other objective. However there exists number of trade-off solutions between the two extreme optimal, that each are better with regards to one objective.

Convexity is an important issue in multi-objective optimization problems, where in non-convex problems the solutions obtained from a preference-based approach will not cover the non-convex part of the trade-off curve. Moreover many of the existing algorithms can only be used for convex problems. Convexity can be defined on both of spaces (objective and decision variable space). A problem can have a convex objective space while the decision variable space is non-convex.

3.2.1 Pareto- optimal set and pareto front

A solution is pareto-optimal if it is not dominated by any other solution in decision variable space. The pareto-optimal is the best known solution with respect to all objectives and cannot be improved in any objective without worsening in another objective. The set of all feasible solutions that are non-dominated by any other solution is called the pareto-optimal or non-dominated set. If the non-dominated set is within the entire feasible search space, it is called globally pareto-optimal set.

The values of objective functions related to each solutions of a pareto-optimal set is called pareto-front. Figure illustrates a typical pareto-front of a two objective minimizing type optimization problem in objective space. Since the concept of domination enables comparison of solutions with respect to multi-objective optimization algorithms practice this concept to obtain the non-dominated set of solutions, consequently the pareto-front.

Chapter 4

Configuration and Problem Formulation

In this thesis, three power system configurations are considered and compared for an offshore construction vessel. In all configurations, DC grid is assumed in order to estimate fuel saving and emission reduction potential by allowing engines to run at optimal speed.

The objective of this study is to develop an evaluation tool to determine which configuration is more beneficial under certain criteria such as fuel consumption, as well as compare configurations with high- and low-power engines.

4.1 Vessel load and power system specification

Offshore Construction Vessel (OCV) is capable of performing subsea construction and equipment installation as well as inspection, maintenance and repair and Remotely Operated Vehicles (ROV) services. Important features of such vessels are sufficient stability that allow station keeping and roll dampening, and good sea keeping performance that provides a safe platform for crew and cargo during operation. It has high demands on the flexibility, efficiency and reliability, and thus is beneficial to have DC grid hybrid power system. Therefore, OCV is chosen in this case study.

Figure 4.1 shows an example of OCV which has been designed by Ulstein to address the latest demands of the subsea installation and deep water remote intervention. It is equipped with an ROV garage, large deck area that allow storage of equipment during transit and large crane. Moreover, it has a diesel electric propulsion system.

Figure 4.1: Offshore construction vessel Viking Poseidon. Courtesy: Ulstein (2017)

4.1.1 Vessel load specification

Station keeping capability is required to maintain the OCV's position during offshore construction operations. Station keeping performance is essential not only for safety (collision, diving operation, etc.), but also for less waiting time for weather windows and efficiency of the operations. Therefore, DP systems for station keeping has become standard for offshore installation vessels, which is a computer-controlled system and can maintain a vessel's position and heading by using its own propellers and thrusters. DP system is considered as one of the critical systems on board a offshore construction vessel.

The offshore construction vessel in this study is equipped with two main propeller ($2 \times 3000kW$), two bow thrusters ($2 \times 1335kW$) and two azimuth thrusters ($2 \times 850kW$). Other loads such as lifting and ventilation is considered to be up to $60kW$. Therefore, the maximum total load is 10.43 MW.

This propulsion system ensures the redundancy as what is required by DP2 , which is loss of position is not occur in the event of a single failure specified in Sec.2.6.1 (DNV-GL (2011)). A DP2 or DP3 system guarantees high uptime to both FPSO and production platforms, for twenty-four hours a day, under challenging conditions.

4.1.2 Power system specification

MCR of the power system can be calculated based on the total loads and typical efficiency from these loads to the diesel engine shaft. The efficiency from thruster loads and other loads to the engine shaft is assumed as 90%, taking efficiency of motor, frequency converter, rectifier and generator into account. Hence, the maximum loading of the diesel engines is,

$$10.43MW/0.9 = 11.59MW \tag{4.1}$$

This could be provided by 2 engines and also more engines. It should be noted that a realistic design will typically choose to use 4-6 engine sets to enhance the general performance of a vessel while optimize total cost. In our case, we are interested to compare the configuration with large power-rating engines and medium-small power-rating engines. On the other hand, there is limited accessible data for fuel consumption mapping and NOx emission mapping of engine. Based on available data, we developed configurations as below.

- Configuration 1 - Two middle speed engines (Rolls Royce Bergen B32:40V12A) with ESD, where power rating of each engine is 6000 kW.

- Configuration 2 - Eight middle speed engines (Rolls Royce Bergen B32:40L3) with ESD, where power rating of each engine is 1500 kW.

- Configuration 3 - Thirty middle speed engines (Perkins 2506C) with ESD, where power rating of each engine is 400 kW.

Based on the information from Perkins and Rolls-Royce, engines involved in this study have characteristics as what can be summed up as in the table below. It is clear that both Bergen engines has better overall fuel efficiency than the Perkins 2506C engine, which may be caused by different designs and technologies such as valve timing, injector and combustion chamber design. Therefore, it is important to notice that the optimal specific fuel consumption in configuration 3 is 12.2% higher than in the other two configurations.

Table 4.1: Engine characteristics

	Engine type	Minimum SFC	Maximum SFC
Bergen B32:40V12A	4-stroke diesel engine	180 $g/kW \cdot h$	250 $g/kW \cdot h$
Bergen B32:40L3	4-stroke diesel engine	180 $g/kW \cdot h$	250 $g/kW \cdot h$
Perkins 2506C	4-stroke diesel engine	205 $g/kW \cdot h$	245 $g/kW \cdot h$

4.2 Single line diagram of configurations

Proposed system configurations are illustrated as single line diagrams in figure 4.2 and 4.3 and 4.4.

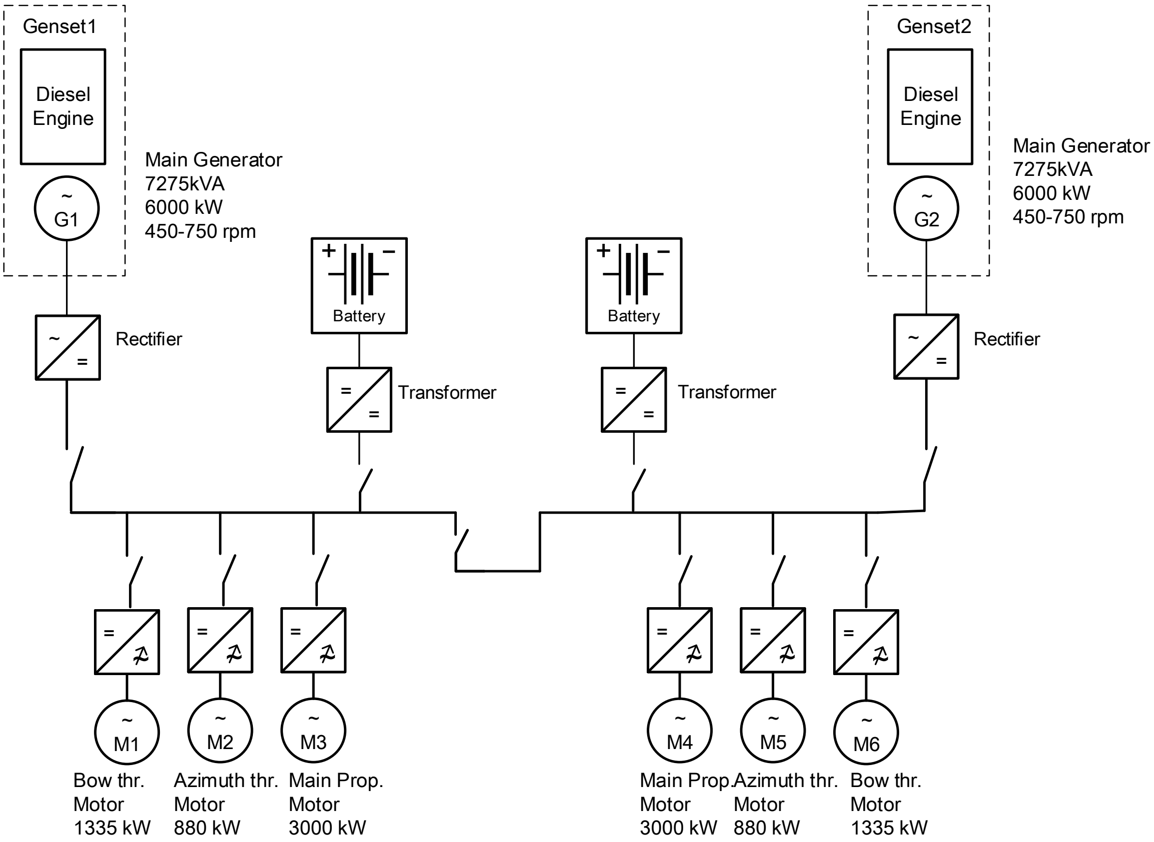


Figure 4.2: Configuration 1 with 2 Rolls Royce Bergen B32:40V12A engines

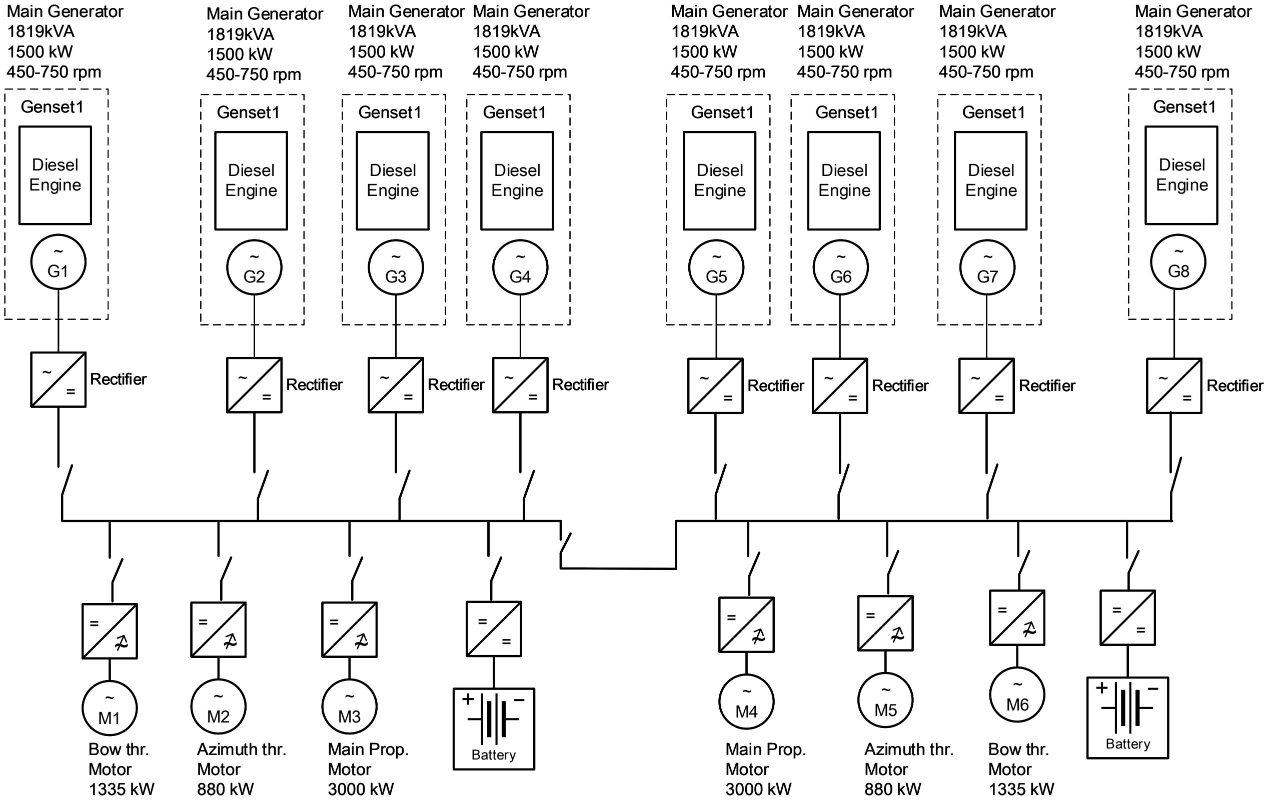


Figure 4.3: Configuration 2 with 8 Rolls Royce Bergen B32:40L3 engines

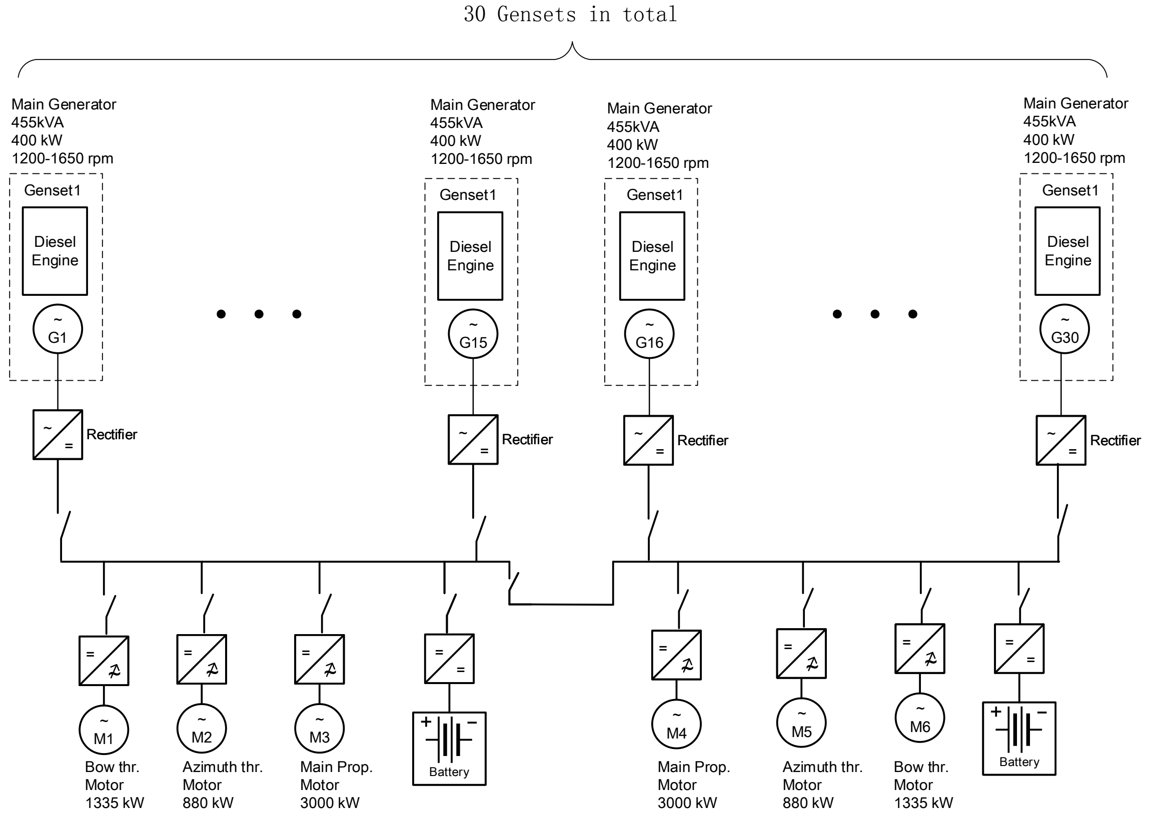


Figure 4.4: Configuration 3 with 30 Perkins 2506C engines

4.3 Optimization problem formulation

To reduce fuel consumption and emission, it is important to make sure that the engines run at optimal operating points under different power demands. Therefore, the objective can be concluded as minimize fuel consumption, denoted by F, and NOx emission, denoted by N.

4.3.1 Optimization problem 1

Due to DC distribution in all configurations, individual engine speed and torque can be adapted to achieve optimal performance regarding to fuel consumption or NOx emission at certain load. Moreover, as a result of multiple gensets, engines can be started or shut down so the remaining engines can run optimally. Therefore, for each engine there are three variables, which are engine speed, engine torque, and engine status (on/off). These design variables are denoted by vectors as following

$$\boldsymbol{\omega} = (\omega_1, \omega_2, \dots \omega_m) \tag{4.2}$$

$$\boldsymbol{T} = (T_1, T_2, \dots T_m) \tag{4.3}$$

$$\boldsymbol{s} = (s_1, s_2, \dots s_m) \tag{4.4}$$

ω_i denotes speed of engine i, while there are m engines in total; T_i and s_i denotes torque and status of engine i, respectively. Both engine speed and engine torque are continuous variables in the operational region of a engine, however, the status of a engine is a discrete variable which is limited to be 0 (off) or 1 (on).

Although the discrete variable problem appears to be easier to solve than the continuous one (since fewer possible solutions exist), in general, it is more difficult to solve except in some trival cases. This is due to the fact that the discrete design space is disjoint and non-convex.

Steady state engine map

The energy production efficiency of a diesel engine can be expressed as SFC, which can be calculated by

$$SFC = \frac{FC}{P} \tag{4.5}$$

where FC is the fuel consumption rate in grams per second; P is the engine power produced in kilowatts, which can be expressed as

$$P = T \cdot \omega \tag{4.6}$$

where ω is angular speed of engine in radians per second; T is the engine torque in newton meters. Besides, specific NOx emission can be calculated by

$$SNOx = \frac{NOx}{P} \tag{4.7}$$

SFC and NOx emission is dependent on many variables such as engine mean effective pressure, engine angular speed and engine power. An engine SFC curve and SNOx curve against cylinder power and speed is generally obtained by running experiments at different operating points. In this study, engine SFC map and SNOx map used is a courtesy from Hybrid Power Lab and resource from Osen (2016). Linear interpolation is used on this maps to search for optimum operating points. The maps are shown in appendix A.

Constraints

Constraints in this problem are mainly power demands, that is, the power produced by all engines should be equivalent to the power required from load. In a strict way, this power constraint is an equality constraint. In practice, this can be regarded as an inequality constraint since power demand may vary, as well as ESD can supply power difference. Therefore, the power constraint can be set between the maximum power demand P_H and minimum power demand P_L for each load power P. It should be noted that the differences between P and P_L, P_H should not exceed the charging/discharging power of the ESD equipment. Another constraint is due to the limited operating area of engine. That is to say an engine can only produce limited power for a given speed, and higher power demand will require high speed.

Single objective optimization problem formulation

From the above information, the final formulation of the optimization problem can be mathematically represented by

$$\begin{aligned}
\text{Minimize}\quad & F(\boldsymbol{\omega},\boldsymbol{T},\boldsymbol{s})=\sum_{i=1}^{m} s_i\cdot\omega_i\cdot T_i\cdot SFC(\omega_i,T_i)\\
\text{subject to}\quad & P_L\le\sum_{i=1}^{m} s_i\cdot\omega_i\cdot T_i\le P_H\\
& T_i\le a\cdot\omega_i+b,\ i=1,\dots,m\\
& T_i,min\le T_i\le T_i,max\\
& \omega_i,min\le\omega_i\le\omega_i,max\\
& s_i\in\{0,1\}
\end{aligned}$$

and

$$\begin{aligned}
\text{Minimize}\quad & N(\boldsymbol{\omega},\boldsymbol{T},\boldsymbol{s})=\sum_{i=1}^{m} s_i\cdot\omega_i\cdot T_i\cdot SNOx(\omega_i,T_i)\\
\text{subject to}\quad & P_L\le\sum_{i=1}^{m} s_i\cdot\omega_i\cdot T_i\le P_H\\
& T_i\le a\cdot\omega_i+b,\ i=1,\dots,m\\
& T_i,min\le T_i\le T_i,max\\
& \omega_i,min\le\omega_i\le\omega_i,max\\
& s_i\in\{0,1\}
\end{aligned}$$

Multi-objective optimization problem formulation

From the above information, the final formulation of the optimization problem can be mathematically represented by

$$\begin{aligned}
\text{Minimize}\quad & [F(\boldsymbol{\omega},\boldsymbol{T},\boldsymbol{s}),N(\boldsymbol{\omega},\boldsymbol{T},\boldsymbol{s})]\\
\text{subject to}\quad & P_L\le\sum_{i=1}^{m} s_i\cdot\omega_i\cdot T_i\le P_H\\
& T_i\le a\cdot\omega_i+b,\ i=1,\dots,m\\
& T_i,min\le T_i\le T_i,max\\
& \omega_i,min\le\omega_i\le\omega_i,max\\
& s_i\in\{0,1\}
\end{aligned}$$

This is formulation of a general multi-objective optimization problem, and weights can be selected and applied to the objective function in a more specific case.

4.3.2 Optimization problem 2

In this problem, we aim to solve the problem of when should ESD be charged or discharged during a operational period, in order to optimize fuel consumption in a power plant with ESD. We presented two methods, ESD guidance strategy which was presented in Miyazaki and Sørensen (2016) and GA method. First of all, typical operational profile of an offshore construction vessel will be described.

Operational Profile

When a customer, ship owner or operator wants to order a new vessel, a set of requirements and specifications related to type of ship and operation of ship is required. In the process of designing the optimal machinery with the right performance features corresponding to owner's requirements, an accurate operational profile of the vessel is necessary. It should be specified the area the ship will operate and the conditions and regulations for operation in the area. Besides, it is important to know the specific operations the ship is going to perform and for how long duration.

For an offshore construction vessel operating in the Mexican Gulf, a typical operational profile may closely resemble what is shown in table 4.2. This operational profile is made by comparing other profiles available and may vary for different OCV vessels.

Table 4.2: Operational profile example of an offshore construction vessel

Operation	Duration [% of total duration]	Power demand [% of MCR]
In port	10	9
Transit low	10	30
Transit high	5	70-90
DP low	55	10-30
DP high	20	30-60

As it can be seen from table 4.2, the engines operate below 50% load for almost 80% of the time. The operating profile shows variations from very low load to high load and this is very challenging to traditional machinery system design. Diesel electric system has been proven to handle this kind of operating profiles efficiently. In practice, different types of load variations appear at a specific operating profile for an offshore construction vessel. Some are very high while only lasting for seconds, such as propeller ventilation due to waves. Others may last for longer periods as for example sudden need of thrust for small changes in position at DP mode, which is caused by wind, current or other external forces. This will have large influence on the selection of the best-suited machinery system for the specific operation profile and needs to be analyzed thoroughly. However, the scope of this study is focused on static power scenario and hence neglecting the load variations.

In port

When a vessel is in harbor the main power consumer is the low voltage hotel load and loading and offloading equipment. In many cases, auxiliary engine will be started while main engines will be turned off. If the ship has installed a modern hybrid power system with facilities for shore connection, it is able to harvest energy from onshore-generated power. In this way there is no need for any prime movers to run in order to generate power.

Transit

The offshore construction vessels do not necessarily have long distances of transit from shore to offshore installations. Most of power production goes to propulsion at a more or less constant load except when maneuvering in and out of port with smaller load variations due to the use of the thrusters. Steering at full speed leads to a high and uneconomical fuel consumption. Due to demand of construction operation in short time, the vessels have to go at full speed sometimes.

Load and fuel consumption (and emissions) vary with the speed of the vessel. In recent years there has been an increasing focus on optimizing the speed in order to reduce both cost and emissions. The weather and sea conditions play an important role in ship maneuvering, and slow steaming can lead to large reductions in fuel costs and emissions to the air. Slow steaming refers to operate ship at significantly less than its maximum speed, which reduces fuel consumption because the drag imparted by fluid increases quadratically with increase in speed.

Dynamic positioning

Whenever it is necessary to keep the vessel stable, either at a point over ground or in relation to another offshore structure, and mooring is not possible or desirable, the DP system is used. For most of the operations an offshore construction vessel will perform, a DP system is required. Operations vary from loading and offloading at offshore, standby mode, anchor handling, subsea repairs, lifting operations, diving support, to ROV operations and etc.

In DP mode all thrusters are used to keep the vessel in desired position regardless of wind and sea conditions. In calm weather, the power consumption may be as low as 10-20% of total installed power. When the weather gets harsh more thrust is needed and the power demand from the thrusters may be as high as 60%. The transient loads and variations may also vary with as much as 30-40% in short periods of time. Due to high seas, the main propellers or thrusters may come into free air in transit or DP mode in rough weather. This represents the largest load transient for the propulsion system.

4.3.3 ESD guidance strategy - Method 1

This method was presented in Miyazaki and Sørensen (2016) and following derivation illustrates why resulting FC can be calculated by the weighted average of the ESD charging power and discharging power under certain assumptions.

As ESD can both provide and consume power from the system, it is possible to change the load being applied to the generator. If the transmission losses are disregarded, the power produced equals the power consumed by load,

$$P_L + P_{ESD} = P_G \tag{4.8}$$

where P_L and P_{ESD} are the power consumed by load and charged to ESD respectively, and P_G is the power output from generator.

For a long operation period, it is expected that average ESD State of Charge (SOC) is not changed after many charge-discharge cycle, thus it is required that

$$E_C = \int_0^{\tau_C} \Delta_C(t) \cdot \eta_C(t) dt \tag{4.9a}$$

$$E_D = \int_0^{\tau_D} \frac{\Delta_D(t)}{\eta_D(t)} dt \tag{4.9b}$$

$$E_C = E_D \tag{4.9c}$$

where

$$\Delta_C(t) = P_{GC}(t) - P_L(t) \tag{4.10a}$$

$$\Delta_D(t) = P_L(t) - P_{GD}(t) \tag{4.10b}$$

E_C is the energy charged and stored in the ESD while E_D is the energy delivered by it. P_{GC} is the power produced by the generator while charging the ESD, and P_{GD} is the power produced by the generator while ESD is discharging to deliver power. η_C and η_D are charging and discharging efficiency correspondingly, which are values between 0 and 1.

The variables P_{GC}, P_{GD}, P_L, Δ_C and Δ_D can be assumed to be constant during one charge/discharge cycle. Given the ESD charging time τ_C and discharging time τ_D, equation 4.9c can be simplified as

$$\Delta_C \cdot \tau_C \cdot \eta_C = \frac{\Delta_D \cdot \tau_D}{\eta_D} \tag{4.11}$$

The average fuel consumption ($\bar{F}$) is given by the following equation,

$$\bar{F} = \frac{\int_0^{\tau_C+\tau_D} P_G \cdot SFC(P_G, \omega) dt}{\tau_C + \tau_D} \tag{4.12}$$

which can also be written as

$$\bar{F} = \frac{\int_0^{\tau_C} P_{GC} \cdot SFC(P_{GC}, \omega_C) dt}{\tau_C + \tau_D} + \frac{\int_{\tau_C}^{\tau_C+\tau_D} P_{GD} \cdot SFC(P_{GD}, \omega_D) dt}{\tau_C + \tau_D} \tag{4.13}$$

where ω, ω_C and ω_D are the engine rotational speed at corresponding scenarios. $SFC(P_G, \omega)$ is the engine instantaneous specific fuel consumption corresponding to generator power and engine speed.

Assuming that P_{GC}, ω_C, P_{GD} and ω_D are constant during one charge-discharge cycle. Substituting equation 4.9c into equation 4.13, as well as using fuel consumption $FC(P, \omega)$ instead of SFC, which results in

$$\bar{F} = \frac{FC(P_{GC}, \omega_C) \cdot \Delta_D + FC(P_{GD}, \omega_D) \cdot \Delta_C \cdot \eta_C \cdot \eta_D}{\Delta_D + \Delta_C \cdot \eta_C \cdot \eta_D} \tag{4.14}$$

Equation 4.14 implies that the resulting FC is calculated by the weighted average of the points $FC(P_{GC}, \omega_C)$ and $FC(P_{GD}, \omega_D)$, as long as the assumptions made are met. Therefore, it is possible to search for the optimal pairs which leads to optimal average fuel consumption under certain load according to the equation. In order to calculate the total fuel consumption for a typical operation of the vessel, optimal fuel consumption under different loads are summed up.

4.3.4 ESD guidance strategy based on GA - Method 2

The optimization problem is how to arrange ESD charge/discharge power during operation so total engine fuel consumption can be minimized. Method 2 is to solve this problem as a single objective optimization problem via GA method. The operation duration can be divided into m small duration where each duration (d_j) operates at the same average load ($P_{L,j}$). At each duration ESD charges or discharges at power $P_{ESD,j}$.

Relationship can be established between fuel consumption and power generated from power plant when ESD charges/discharges by sampling in the data space and linear interpolation. Besides, it is assumed that the ESD SOC is not changed after a typical operation.

$$\begin{aligned}
\text{Minimize} \quad & f = \sum_{j=1}^{m} FC(P_{ESD,j}, L_j) \cdot d_j \\
\text{subject to} \quad & -E_{ESD} \leq \sum_{j=1}^{n} P_{ESD,j} \cdot d_j \leq E_{ESD},\ n = 1, \ldots, m \\
& \sum_{j=1}^{m} P_{ESD,j} \cdot d_j = 0
\end{aligned}$$

Chapter 5

Case Study

All the case studies have been carried out during this study are realized via Matlab. Average computing time for single objective optimization problem is around 100 second, while around 3000 s for multi-objective optimization problem. Setting are shown in each case.

5.1 Fuel consumption at static load

The first case to be studied is a single objective optimization problem when gensets operate at static load demand, which are loads from 10% to 100% MCR with an interval of 10%.

The simulation setting is shown in table below.

Table 5.1: Simulation setting for optimization of FC at static load

	Variables	Population size	Iterations	Function tolerance
Configuration 1	4	50	100	10^{-3}
Configuration 2	24	100	150	10^{-5}
Configuration 3	90	200	200	10^{-5}

In figure 5.1, 5.2 and 5.3, results from simulations are shown. In this case, the consumed static load varies from 10% to 100% and it is assumed at least 2 gensets must be in operation for the sake of safety and redundancy requirement.

At low loading rate which equals to 10%, configuration consists of 30 Perkins gensets (configuration 3) has as good performance in fuel consumption as configuration consists of 8 lower power-rating Bergen gensets (configuration 2). Fuel consumption resulted from 2 high power-rating

Bergen gensets (configuration 1) is higher than in the other two configurations by approximately 50 000 g/h.

As static load increases, fuel consumption increases faster for configuration 3 than for the other two configurations. At static load around 15% MCR, configuration 1 and 3 have almost equal fuel consumption. After this point, performance of configuration 3 deteriorates largely, which ends up with a larger fuel consumption around 300 000 g/h compared with configuration 2 at 100% MCR. It makes sense since the optimal SFC of Perkins genset is 25 g/kWh higher than the other two Bergen gensets, which is 12.2% percent higher than its optimum. On the other hand, as the two different Bergen engines have the same fuel consumption characteristics and the only difference is cylinder number, fuel consumption at high load for these two configurations are almost the same. However, with stopping unnecessary engines, configuration 2 outperform configuration 1 at load which is lower than 50% of the maximum rated load.

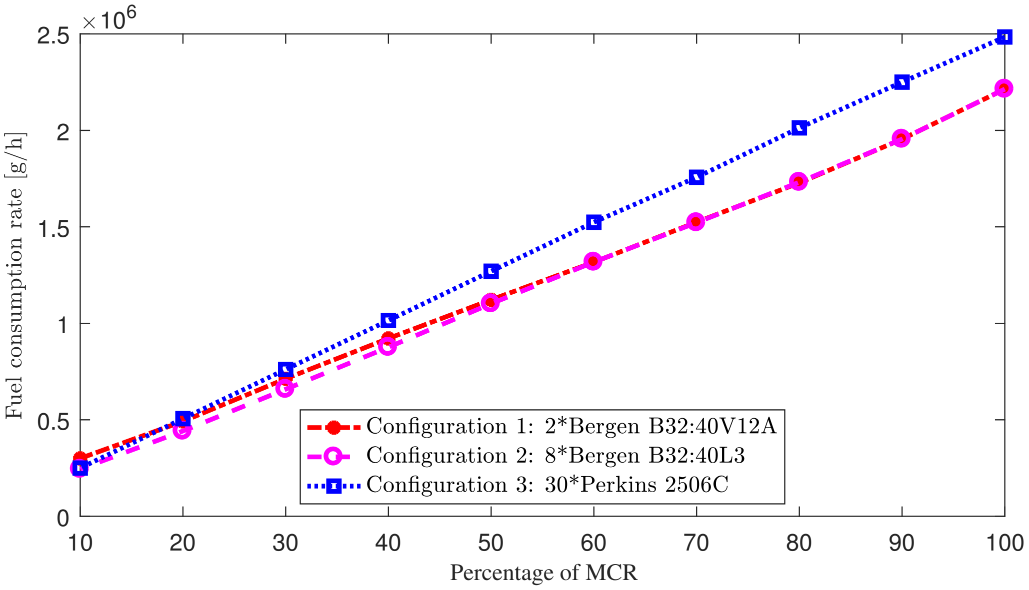


Figure 5.1: Fuel consumption of 3 configurations at static load

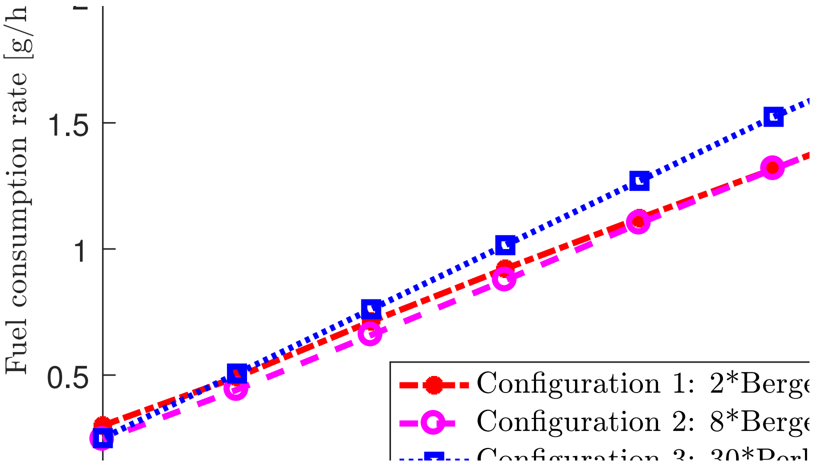


Figure 5.2: Zoom view of figure 5.1

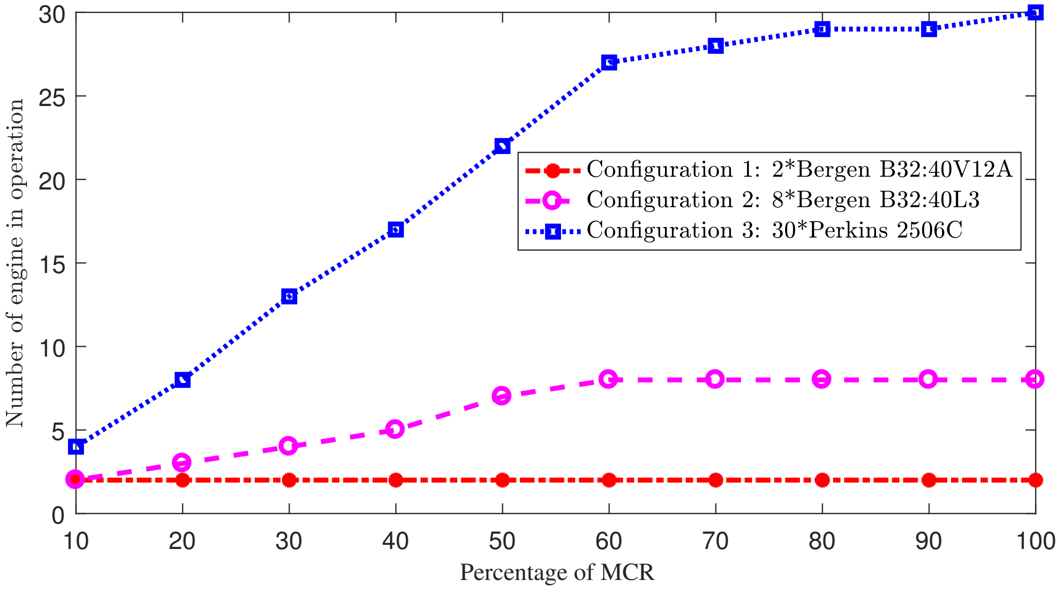


Figure 5.3: Engine number of 3 configurations at static load

Figure 5.3 illustrates the number of running engine in different configurations. It is clear that both engines must work at whole load range in configuration 1, ensuring safety and redundancy in worst case. For the other two configurations, operated engine number changes slightly at high load and drops quickly after loading rate 60%. The reason for this is less engine sharing the same load can lead to more optimal operating condition for every single engine and hence fuel consumption.

5.2 Sensitivity analysis

Due to limited computation time and also the stochastic searching characteristic of GA method, the optimization sets vary slightly while leading to same cost functions. During a real operation, there exists fluctuation both in engine speed and torque, despite that it is given a constant static load. Therefore, it is very important to guarantee the validity of optimization sets and resulted optimum when fluctuation in engine speed and torque is considered. A study case based on Bergen B32:40V12A configuration is established in order to know how to choose a optimal candidates from many candidates and analyze the sensitivity.

In this case study, 2 Bergen B32:40V12A engines in configuration 1 were required to deliver 8.4 MW power in total. Simulation setting is the same as what is shown in table 5.1. Results from ten different runs are shown in 5.2. ω_1 and ω_2, T_1 and T_2, and P_1 and P_2 are speed, torque and power of engine 1 and 2 respectively.

Table 5.2: Configuration one at 70% load (8.4 MW)

	ω_1	ω_2	T_1	T_2	P_1	P_2	Fuel consumption
No.1	668 rpm	663 rpm	66.4 kNm	53.9 Nm	4.65 MW	3.75 MW	1.52 tonne/h
No.2	651 rpm	650 rpm	61.9 kNm	61.3 Nm	4.22 MW	4.18 MW	1.52 tonne/h
No.3	674 rpm	653 rpm	61.4 kNm	59.3 Nm	4.34 MW	4.06 MW	1.52 tonne/h
No.4	666 rpm	660 rpm	63.3 kNm	57.5 Nm	4.42 MW	3.98 MW	1.52 tonne/h
No.5	668 rpm	659 rpm	645.5 kNm	56.2 Nm	4.52 MW	3.88 MW	1.52 tonne/h
No.6	675 rpm	663 rpm	62.2 kNm	57.6 Nm	4.4 MW	4.0 MW	1.52 tonne/h
No.7	6675 rpm	629 rpm	64.7 kNm	58.0 Nm	4.57 MW	3.83 MW	1.52 tonne/h
No.8	661 rpm	659 rpm	64.3 kNm	57.1 Nm	4.45 MW	3.95 MW	1.52 tonne/h
No.9	669 rpm	631 rpm	64.3 kNm	58.9 Nm	4.50 MW	3.90 MW	1.52 tonne/h
No.10	667 rpm	660 rpm	66.3 kNm	54.5 Nm	4.63 MW	3.77 MW	1.52 tonne/h

It can be seen that the optimal fuel consumption from ten runs are quite consistent, while engine speeds and torques vary slightly. Hence, it is interesting to see how well each dataset will perform when input parameter varies. Here we take a look at results from Monte Carlo simulations where the mean values of input parameters are from run 2 and run 5.

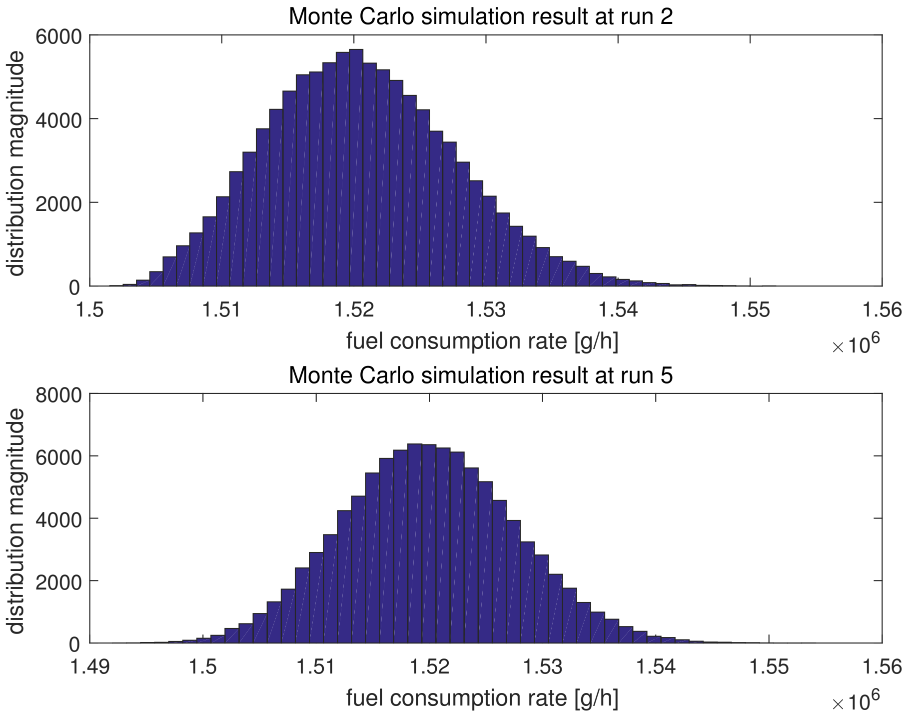


Figure 5.4: Monte Carlo simulation for run 2 and 5, mean value for speed and torque is the value from run 2 and 5; standard deviation for speed is 5 rpm while 50 Nm for torque. Total case number is 100000. Normal distribution was applied.

Figure 5.4 illustrates the distribution from the sensitivity analysis when speed and torque vary. In both cases the shape of distribution is very close to normal distribution. Mean value of fuel consumption is 1.5205 tonne per hour at run 2 while 1.52 tonne per hour at run 5; Standard deviation of fuel consumption is 7.0544 kg per hour at run 2 while 7.5898 kg per hour at run5. It can be concluded that for optimization datasets and results in both runs the mean values keep almost the same, despite the varying of engine speed and toque. The performance from both datasets can be regarded good and acceptable. As long as the optimization objective is valid despite of small variations in its input parameters, it is reasonable to say the GA optimization yields a satisfactory result.

5.3 Efficiency degradation

As what is mentioned in section 2.1.4, efficiency across the load range is very important. The converter efficiency curve we used in this case is shown as in figure 2.3. In this simulation study, we modified the engine power in the constraints to include converter efficiency degradation.

The set up of simulation is the same as what has shown in table 5.1. The results is displayed in table 5.3 and figure 5.5.

Table 5.3: Fuel consumption comparison (in kg/h) before and after including η_c

Load(%MCR)	20	30	40	50	60	70	80
Configuration 1	492	706	901	1122	1320	1523	1730
Configuration 2	442	658	876	1108	1318	1520	1727
Configuration 3	506	761	1015	1270	1524	1757	2013
Config.1 (incl. η_c)	550	759	955	1179	1378	1593	1805
Config.2 (incl.η_c)	465	688	913	1155	1362	1587	1804
Config.3 (incl.η_c)	518	779	1038	1295	1560	1814	2062

The total shape and trend of curves in figure 5.5 is very similar as in figure 5.1. However, we can see there are some differences if we take a close look at low to middle load. At 20% MCR, configuration 1 used to have slightly lower fuel consumption than configuration 3. The situation changes when converter efficiency degrading is considered, where fuel consumption in configuration 3 is 6% less than in configuration 1. The cross-point where fuel consumption in configuration 1 and 2 approximately equals used to be 60% MCR without considering converter efficiency change, which now increases to 80%. This indicates the advantage that high-power engines have at high load is weaken when efficiency degradation is taken into account. Comparing before and after considering η_c, fuel consumption increased at highest 11% in configuration 1, 5% in configuration 2 and only 2.3% in configuration 3; Besides, fuel consumption increased 4.2%, 4.3% and 2.4% in configuration 1, 2, and 3 respectively when delivering 80% MCR power.

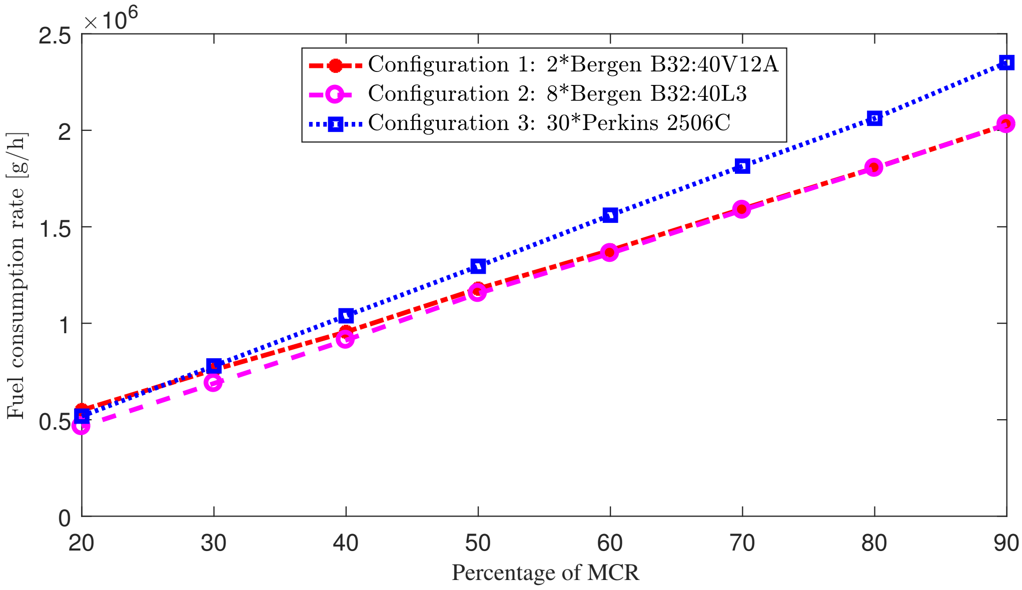


Figure 5.5: Efficiency degradation

Comparing figure 5.6 with 5.3, one can tell that the numbers of engine in operation in configuration 1 and 2 have exactly kept the same. However, the number of engine which is running in configuration 3 increases, particularly at low load. For example, engine number increased from 8 to 9 at 20% MCR. This may be caused by more optimal fuel efficiency to start another engine when engine load increases by a small step.

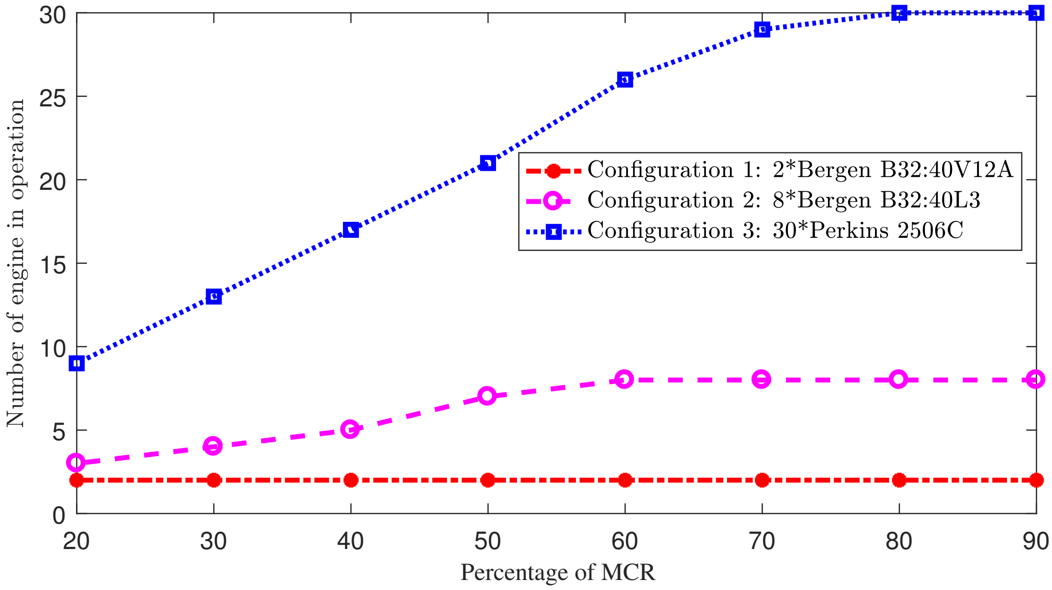


Figure 5.6: Efficiency degradation

5.4 Multi-objective optimization

The NOx control requirements of MARPOL Annex VI provide for progressive reductions in NOx emissions from marine diesel engines. NOx emissions are restricted to certain limits (Tier I, II and III) based on the ship's construction date and area of operation. Within each of these Tiers, the NOx emission limit is set based on the ship's rated engine speed as shown in figure 5.7. If ship's operation violates the rules, high penalty will be charged or the vessel will even not be allowed to operate in the area anymore. Hence, NOx emission is of high importance to ship operation asides from fuel consumption.

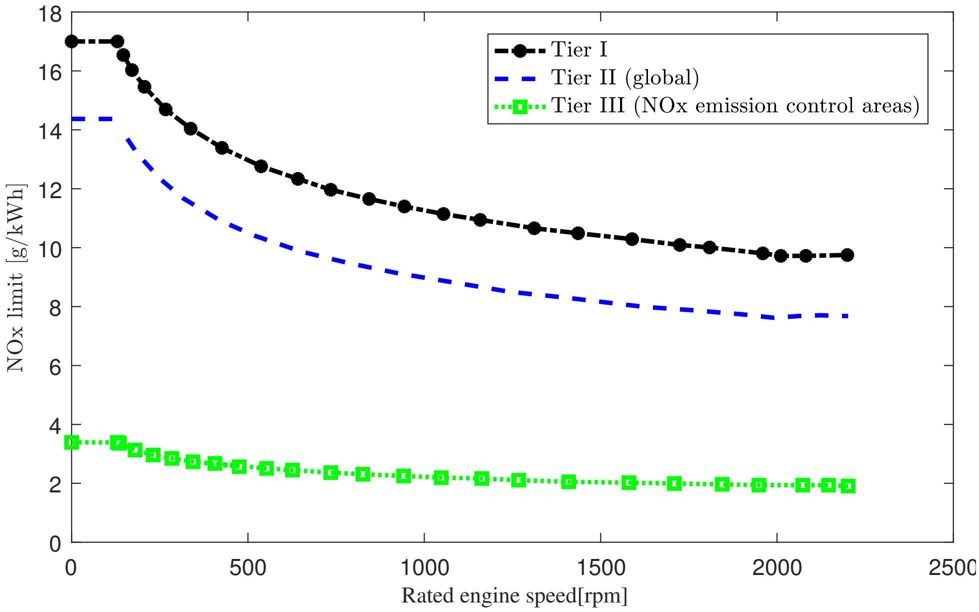


Figure 5.7: MARPOL Annex VI NOx emission limits. Data curtesy: MARPOL.

Tier I and Tier II limits are global, while the Tier III standards apply only in NOx Emission Control Areas (ECA). Tier II standards are expected to be met by combustion process optimization, which can be achieved by adjusting injection timing, pressure, and rate, fuel nozzle flow area, exhaust valve timing, and cylinder compression volume. However, most of these mentioned strategies result in higher fuel consumption. As the goal of this study is apply optimization method and compare the power system design, it is desirable to set NOx emission as a optimization objective instead of a constraint. In practical cases, NOx emission can be set both as a objective and a constraint to make sure the operation comply with the emission regulation.

Corresponding to the method which has been introduced in section 4.3.1, we conducted multi-objective optimization for configuration3: Perkins 2506C engines at 3 different load conditions (20%, 40% and 70% MCR). The setting of this simulation is indicated in table 5.4.

Table 5.4: Simulation setting for multi-objective optimization

	Variables	Population size	Iterations	Function tolerance
Configuration 3	90	200	200	10^{-5}

Osen (2016) has shown that a typical offshore construction vessel operates at load lower than 60% MCR during around 80% of its operating time. Therefore, we chose three load points to study in multi-objective optimization, which are 20%, 45% and 60%. More simulations have run for other loading condition and results are shown in appendix B.

5.4.1 20% load

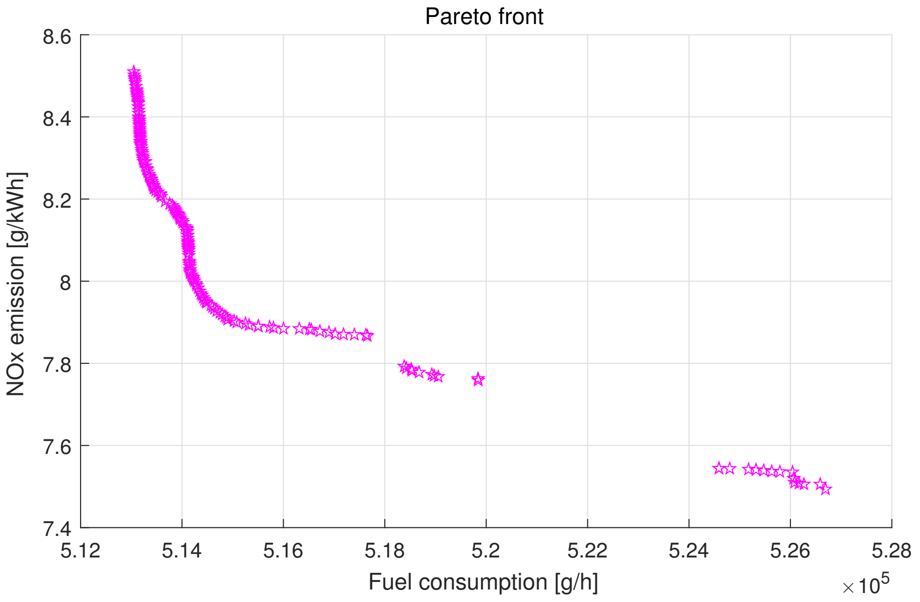


Figure 5.8: Multi-objective optimization result at 20% MCR

Figure 5.8 depicts a resulted pareto front from this case and it provides possible optimal candidates, which can be chosen according to different criteria.

The fuel consumption at 20% load only minimizing fuel consumption is 506 kg/h. After taking NOx emission into consideration, fuel consumption increases and varies from 513 to 527 kg/h as can be seen from figure 5.8. Besides, NOx emission varies from 7.5 to slightly over 8.5 g/kWh, which is roughly within the NOx limit range of Tier II (global). The figure shows a pareto front which consists of non-dominating result datasets. All the points in pareto front, which is marked in star shape, are optimal candidates considering different weight placed on reduction of NOx emission and decrease of fuel consumption. For example, when only considering to minimize the NOx emission, it will lead to fuel consumption of 527 kg/h and NOx emission of 7.5 g/kWh; when considering minimize NOx emission, it gives fuel consumption of around 527 kg/h and

NOx emission of 7.5 g/kWh. Therefore, improvement of one objective function will accompany the deterioration of the other. Besides, it can be noticed that NOx emission decreases rapidly when fuel consumption rate increases from 513 kg/h to 515 kg/h, after which the compromise on fuel consumption is required to be much larger to achieve the same amount of NOx reduction. Therefore, it may be very beneficial to choose the turning point around (515 kg/h, 7.9 kg/kWh) as operational point, as fuel consumption does not compromise much to achieve low NOx emission.

5.4.2 45% load

Higher fuel consumption appears in results at 45% load compared to 20% load, which ranges from 1052 kg/h to slightly higher than 1059 kg/h. However, lower NOx emission occurs in this cases than in the case where power requirement is around 20% maximum load, which is from approximately 7.25 to 8.05 g/kWh. Unlike figure 5.8, there is not many turning points in figure 5.9. In another word, the deterioration of NOx emission for improving fuel consumption is very similar through whole range. Therefore, it will be more difficult to choose the optimal point if there is no clear idea about how to distribute weight on two optimization objectives.

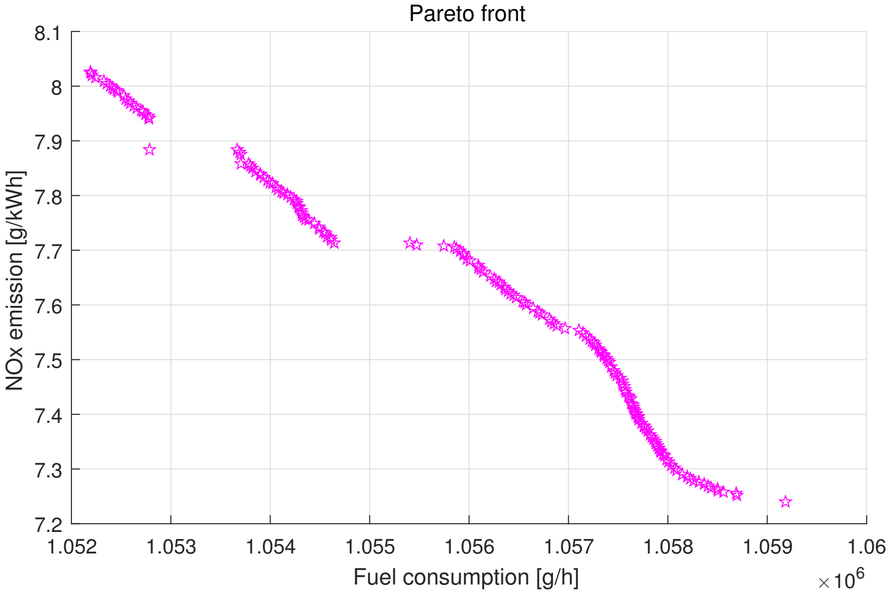


Figure 5.9: Multi-objective optimization result at 45% MCR

5.4.3 70% load

When power plant operates to deliver 70% maximum load, it conducts higher specific NOx emission (seen in figure 5.10). To achieve the minimum fuel consumption, which is 1748 kg/h in this case, the NOx emission will be around 10.62 g/kWh. On the other hand, the fuel consumption will be around 1749.2 kg/h in order to achieve the minimum NOx emission, which is around 10.51 g/kWh. The NOx emission is also within the limit of Tier II. The turning point in this curve appears approximately at (1749.18 kg/h, 10.51 g/kWh), after which NOx emission will decrease rapidly.

This implies it could be difficult to achieve low fuel consumption if there is a strict limitation on NOx emission at 70% MCR.

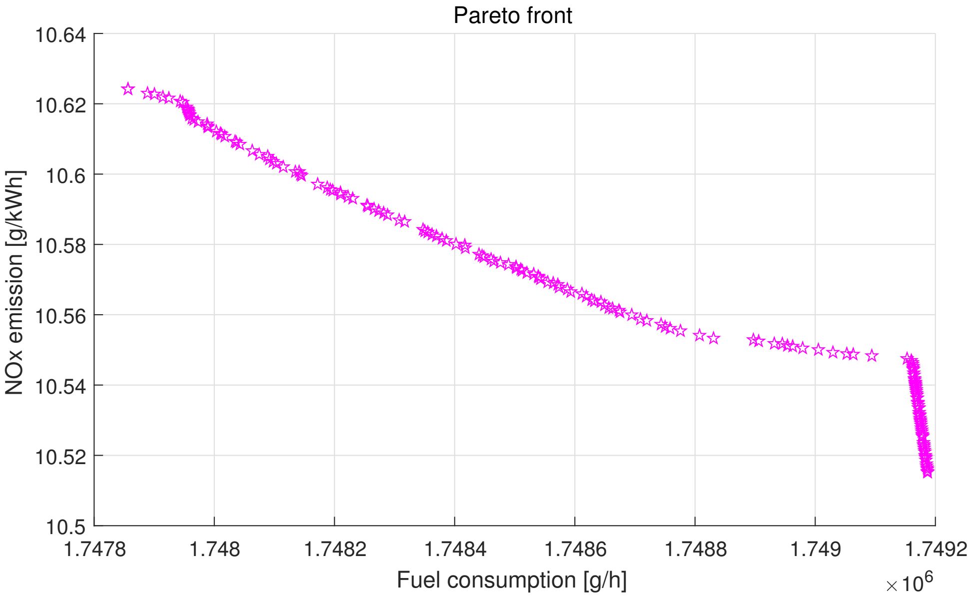


Figure 5.10: Multi-objective optimization result at 70% MCR

5.5 Optimize total fuel consumption with ESD

In this case study, optimization is achieved to estimate fuel saving potential at static power demand. An ESD is considered in all three configurations. ESD maximum charge/discharge power is assumed to be 400 kW, which implies the prime mover can deliver power at more flexible range. It should be noted that to make the fuel consumption results comparable, the power delivered by ESD has also been counted into fuel consumption according to the corresponding optimal SFC as stated in table 4.1. Besides, the optimization objective is modified to be specific fuel consumption.

Table 5.5: Comparison of results for configuration 1 without and with ESD

Load [% MCR]	20	30	40	50	60	70	80	90
FC [kg/h]	492	713	922	1122	1327	1535	1748	1954
SFC [kg/kWh]	205	197	192	187	184	183	182	182
Engine number	2	2	2	2	2	2	2	2
FC (ESD) [kg/h]	472	691	889	1096	1320	1530	1734	1948
SFC (ESD) [kg/kWh]	197	192	185	182.8	183	182	180	182
Engine number (ESD)	2	2	2	2	2	2	2	2

Due to the redundancy requirement in most cases, constraint has been set so that at least two engines are required to operate at same time. Therefore, the ESD usage strategy applied in configuration 1 is strategic loading as no engine in this configuration can be stopped. It is clear that from table 5.5 that the improvements is very small in average, among which the highest reduction of specific fuel consumption is 8 g, which is around 4%. Fuel saving potential is low at the high load due to high fuel economy before the ESD was connected. However, the improvement at the low load is hindered by running two large-power engines at low load and not able to stop one of them. Therefore, it is interesting to test how much improvement can be achieved by allowing one engine to shut down at low load in configuration 1. It should be noted it is not possible deliver load by only single genset during a DP operation.

Table 5.6: Comparison of results for configuration 1 with ESD (considering engine start/stop)

Load [% MCR]	20	30	40	50	60	70	80	90
FC (ESD1) [kg/h]	472	691	889	1121	1320	1530	1734	1948
SFC (ESD1) [g/kWh]	197	192	185	182.8	183	182	180	182
Engine number (ESD1)	2	2	2	2	2	2	2	2
FC (ESD2) [kg/h]	448	659	915	1121	1320	1528	1734	1948
SFC (ESD2) [g/kWh]	187	183	183	182.8	182	182	180	182
Engine number (ESD2)	1	1	1	2	2	2	2	2

In table 5.6, values labeled in ESD1 indicates they are the results from configuration 1 where both engines have to run at same time, while values labeled in ESD2 indicates the scenario where one engine is allowed to start/stop. It can be told that at high loads, there is little changes on results as both engines have to run to deliver enough power. However, one engine will stop when load is lower than 40% MCR when it is allowed. By stopping one engine, fuel economy at low loads have been improved significantly, where the SFC improves by 8 g/kWh (4%), 9 g/kWh (4.6%) and 2 g/kWh (1%) at 20%, 30% and 40% maximum load respectively. The result illustrates the effect of spinning reserve ESD usage (where allowing less genset to connect to the bus) can lead to larger fuel savings than simply operating engines in the optimum set-point (strategic loading ESD usage technique). Recently marine regulations have been developed to allow the usage of ESD as a spinning reserve to ensure redundancy at DP, and it is very promising to improve fuel economy.

Table 5.7: Comparison of results for configuration 2 without and with ESD

Load [% MCR]	20	30	40	50	60	70	80	90
FC [kg/h]	442	658	876	1101	1318	1522	1732	1954
SFC [g/kWh]	184	183	182.5	183.5	183	181	180	181
Engine number	3	4	5	7	8	8	8	8
FC (ESD) [kg/h]	430	648	857	1093	1292	1512	1728	1944
SFC (ESD) [g/kWh]	180	180	180	180	180	180	180	180
Engine number (ESD)	2	3	4	5	6	7	8	8

From table 5.7, it can be seen that specific fuel consumption decreases and achieves optimum when less engine is running. When engines running at low load, it is very beneficial to integrate an

ESD as spinning reserve, as load per genset is increases and thus leading to better fuel efficiency and less emission. At high load such as 80% and 90% MCR, the fuel consumption is slightly lower when gensets operate together with ESD, where the ESD usage technique is strategic loading.

Table 5.8: Comparison of results for configuration 3 without and with ESD

Load [% MCR]	20	30	40	50	60	70	80	90
FC [kg/h]	506	761	1015	1260	1512	1739	1987	2225
SFC [g/kWh]	210	211	211	210	210	207	207	206
Engine number	8	13	17	22	27	28	29	29
FC (ESD) [kg/h]	489	734	980	1228	1474	1721	1965	2214
Engine number (ESD)	7	10	13	18	21	25	28	29
SFC (ESD) [g/kWh]	205	205	205	205	205	205	205	205

In configuration 3, more engines can be stopped at conditions where there is low fuel efficiency. It can be observed in table 5.8 that 6 engines stopped at 60% MCR load to achieve the optimal SFC with the assistance of ESD, which results in a potential fuel saving of 50 kg/h. Besides, by analyzing the engine number, one can tell configuration with low-power engine is very flexible and there exists frequent start and stop of gensets. This is an advantage in terms of achieving better fuel economy, however, it requires a better power management system to govern and control the gensets and avoiding stops and starts which gives insignificant fuel saving.

5.6 Operational profile and fuel consumption

In this part, we will present results from 2 different methods which has been mentioned in section 4.3.2. An ESD (rated power is 400 kW) is considered to charge or discharge power during a typical operation while optimize total fuel consumption during operation period. The variables considered are ESD charge/discharge power along at different time during the operation. Moreover, different ESD energy capacities have been applied in simulations via method 2 in order to see how capacity influences optimization result. A proposed operational profile is described in table 5.9 and depicted in figure 5.11. It should be noted that only average load is considered in this study as engine fuel consumption maps are obtained under static load.

Table 5.9: Operational profile

Operation	Duration [hours]	Load [kW]	Average load [kW]
Demobilization	10	1080	1080
Mobilization	10	1080	1080
Transit (low)	20	3600	3600
Transit (high)	10	8400-9600	8400
DP (low)	132	1200-3600	2400
DP (high)	48	3600-7200	5400

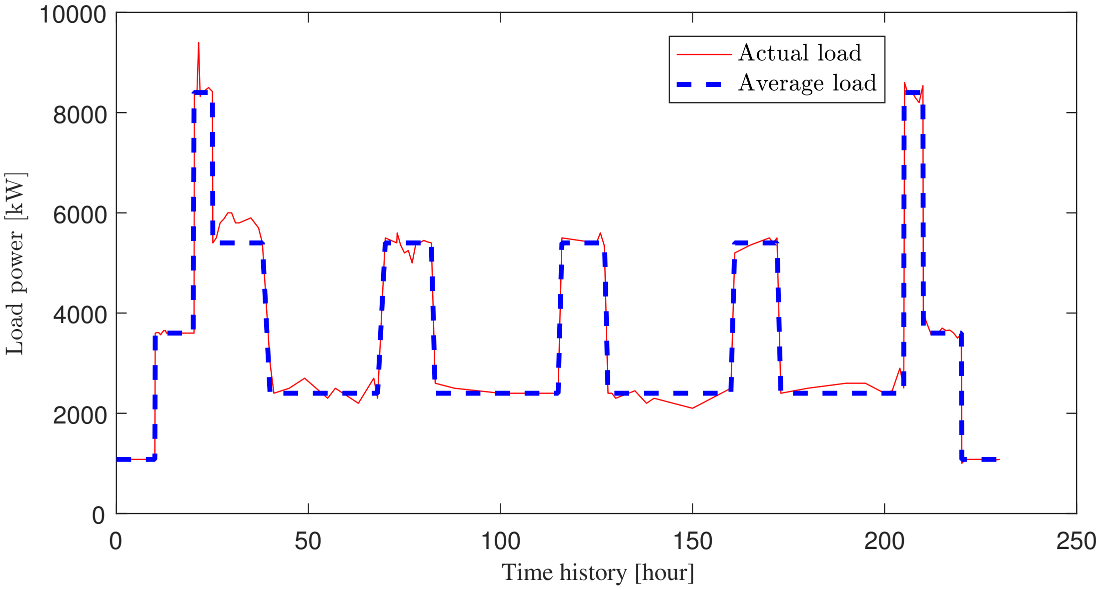


Figure 5.11: Benchmark operational profile

5.6.1 Method 1

Results from this section is based on method mentioned in section 4.3.2. Neglecting charging efficiency (η_C) and discharging efficiency (η_D), equation 4.14 can be written as

$$\bar{F} = \frac{FC(P_{GC}, \omega_C) \cdot \Delta_D + FC(P_{GD}, \omega_D) \cdot \Delta_C}{\Delta_D + \Delta_C} \tag{5.1}$$

which implies that the resulting average FC is calculated by the weighted average of points defined by charging power Δ_C and discharging power Δ_D. Linear interpolation on SFC curves can be used to obtain the optimum points P_{GC} and P_{GD}. By inspecting and searching the sampled points for each static power requirement, it is possible calculate the optimal operational parameters as the set of points of P_{GC} and P_{GD} that leads to the global minimum of $\bar{F}$ for each load P_L. For each load condition, there exists an optimum average fuel consumption calculated by 5.1. Therefore, the total fuel consumption can be the sum of all optimum fuel consumption values at all loads.

The results is shown in table 5.10, 5.11 and 5.12 reveals that by integrating ESD in hybrid power plant reduces fuel consumption by 5.9%, 4.82% and 6.7% in configuration 1, 2 and 3 respectively, during a specified benchmark operation. Configuration 2 have the best performance in terms of fuel saving, and it is 7 tonne and 17 tonne lower than total fuel consumption in configuration 1 and 3. That is to say the total fuel consumption resulted from configuration 2 is 5% and 11.7% lower than what is resulted from configuration 1 and 3. As explained, the optimum SFC of engine which is used in configuration 1 is 12.5% higher than the optimum SFC of engine which is used in configuration 2 and 3. The performance of configuration 3 is not necessarily bad if taking this factor into account.

Table 5.10: Optimization result during an operation with configuration 1

Operation	Mob./Demob.	DP (low)	Transit (low)	DP (high)	Transit (high)
Load [% MCR]	9	20	30	45	70
Duration [hours]	20	132	20	48	10
Δ_C [kW]	400	400	200	400	100
Δ_D [kW]	400	400	200	400	100
Total FC w/ ESD					144098 kg
Total FC w/o ESD					154000 kg
FC improvement					5.9%

Table 5.11: Optimization result during an operation with configuration 2

Operation	Mob./Demob.	DP (low)	Transit (low)	DP (high)	Transit (high)
Load [% MCR]	9	20	30	45	70
Duration [hours]	20	132	20	48	10
Δ_C [kW]	100	100	300	100	400
Δ_D [kW]	100	100	300	100	400
Total FC w/ ESD					137064 kg
Total FC w/o ESD					144000 kg
FC improvement					4.82%

Table 5.12: Optimization result during an operation with configuration 3

Operation	Mob./Demob.	DP (low)	Transit (low)	DP (high)	Transit (high)
Load [% MCR]	9	20	30	45	70
Duration [hours]	20	132	20	48	10
Δ_C [kW]	300	100	100	300	0
Δ_D [kW]	300	100	100	300	0
Total FC w/ ESD					153985 kg
Total FC w/o ESD					165000 kg
FC improvement					6.7%

5.6.2 Method 2

This optimization method has been mentioned in section 4.3.2. Considering ESD charging/discharging power at each time slot is a variable, it is important to divide the operational period into suitable amount so reasonable results can be obtained. Since we assume that the benchmark operational profile is symmetric, it is possible to consider this optimization problem only in the first 135 hours of the whole operation. Here we present results from two different time dividing sizes, 21 time slots (21 variables) in the first case and 115 time slots (115 variables) in the second case.

21 points

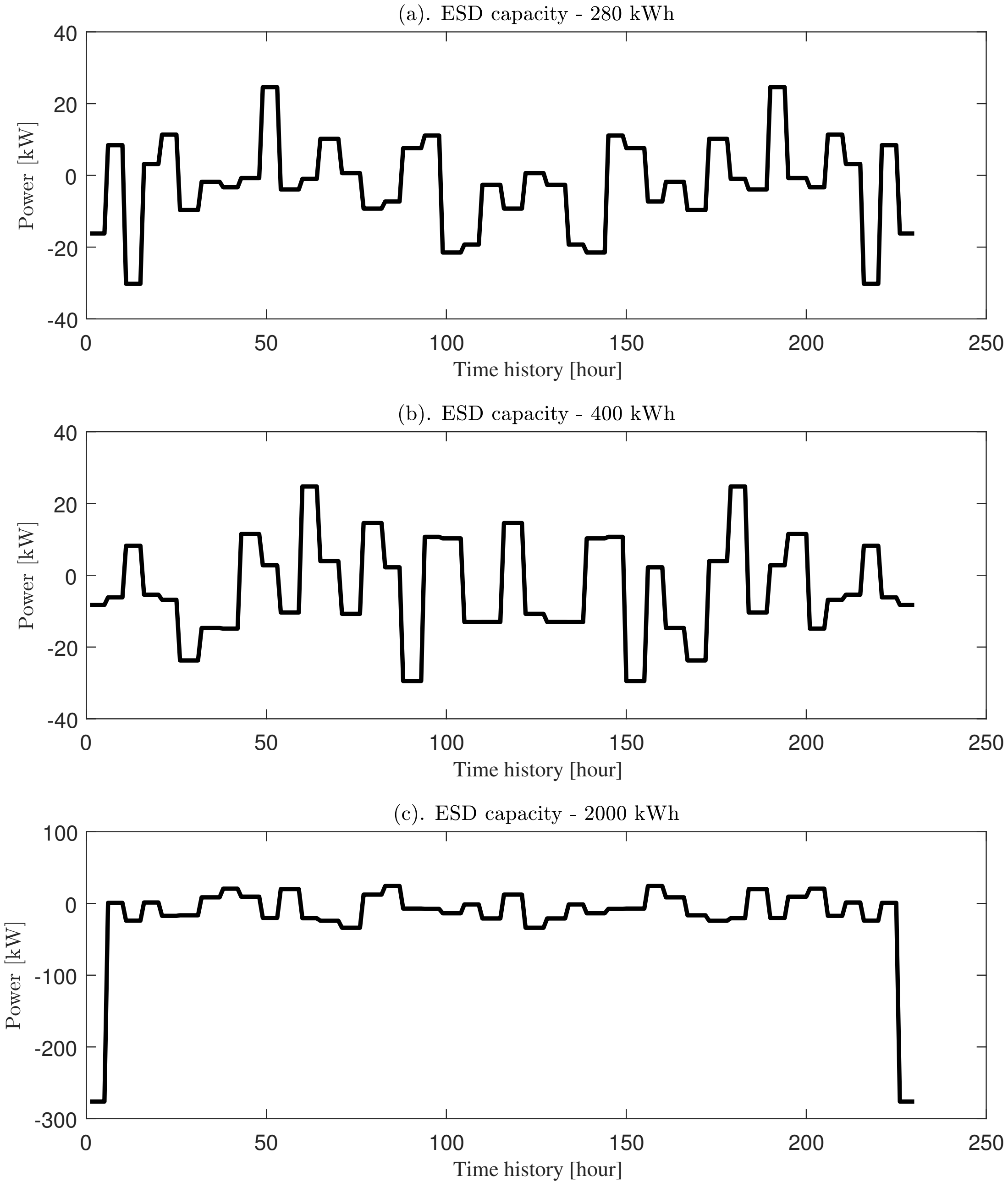


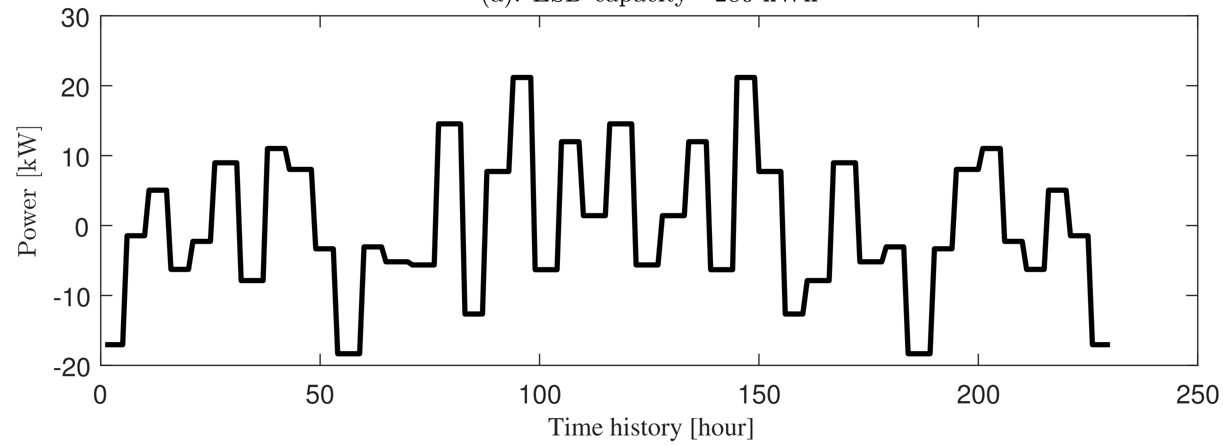
Figure 5.12: Result from optimization of fuel consumption with 21 variables during the benchmark operation in configuration 1.

In this case, only 21 variables are considered, which implies ESD charges or discharges at same constant power for around 5 hours. For each configuration of power plant, 3 different ESD energy capacities are considered: 280 kWh, 400 kWh and 2000 kWh. The first two ESD sizes are rated to match the common battery size for hybrid marine power plant, while the largest ESD size considered also exists in the industry but not very common. The optimization results of ESD charge/discharge power at different time instants is depicted in figures 5.12, 5.13 and 5.14.

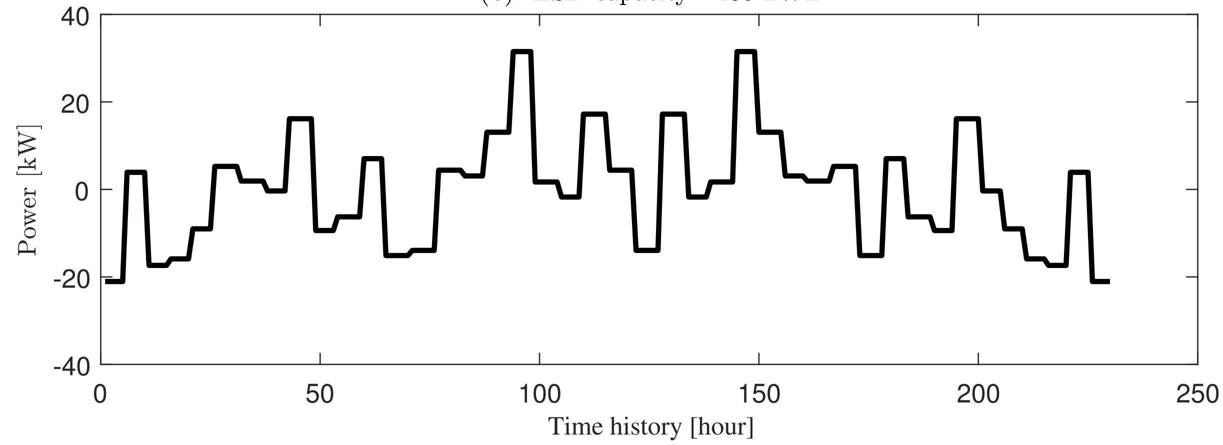
The optimum ESD charging/discharging power at different time instants is different in cases where there are different ESD energy capacities (depicted in figure 5.12). In the case where the energy capacity is 280 kWh, it can be calculated that ESD can be discharged at 56 kW for at most 5 hours continuously. Even though the maximum charge/discharge power of ESD is 400 kW, the constraint is limited by ESD energy capacity and time duration of each variable. Therefore, the optimization result is also limited to an extent. In figure 5.12 (c), a significant power discharge can be seen at the first and last interval, where the ship operates in mobilization and demobilization at port (depicted in figure 5.11). This is reasonable due to the low load (9% MCR) at port, where the fuel economy can be boosted by discharging the ESD.

Figure 5.13 (a) and 5.13 (b) has similar ESD charge/discharge pattern, with two charge peaks around at 100 and 150 hours and discharge peaks at the beginning and the end. The same limitation of charge/discharge power explained in configuration 1 also applies in this configuration. In the figure 5.13 (c), it shows more clear charge/discharge peak at time instants 1, 50, 90, 155, 190 and 230 hours. This is due to the larger charge/discharge power allowed due to its larger ESD energy capacity. When reviewing these mentioned time instants in 5.11, one will find they are the duration where there is DP (low) or mobilization or demobilization. The optimum of total fuel consumption is achieved by charging or discharging ESD, which illustrates the effect ESD has at especially low load.

(a). ESD capacity - 280 kWh



(b). ESD capacity - 400 kWh



(c). ESD capacity - 2000 kWh

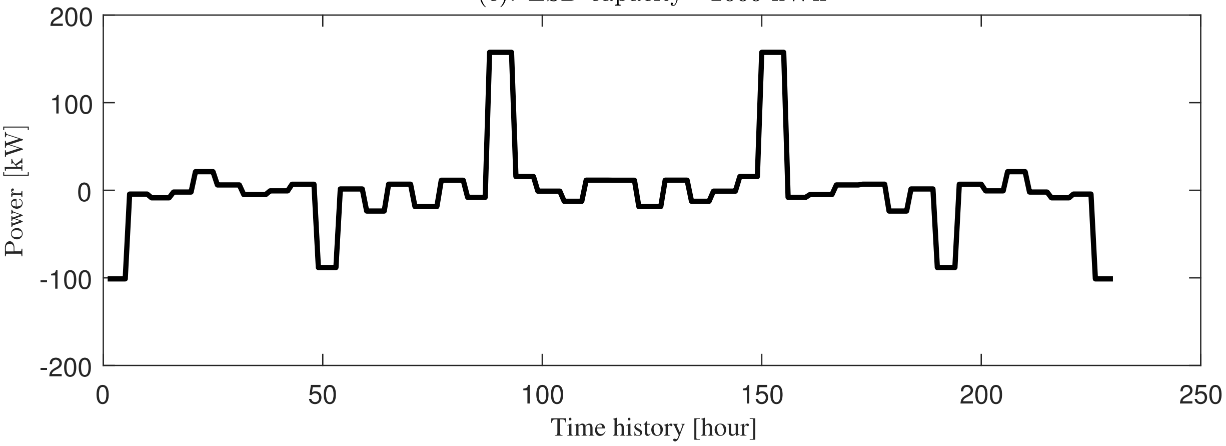
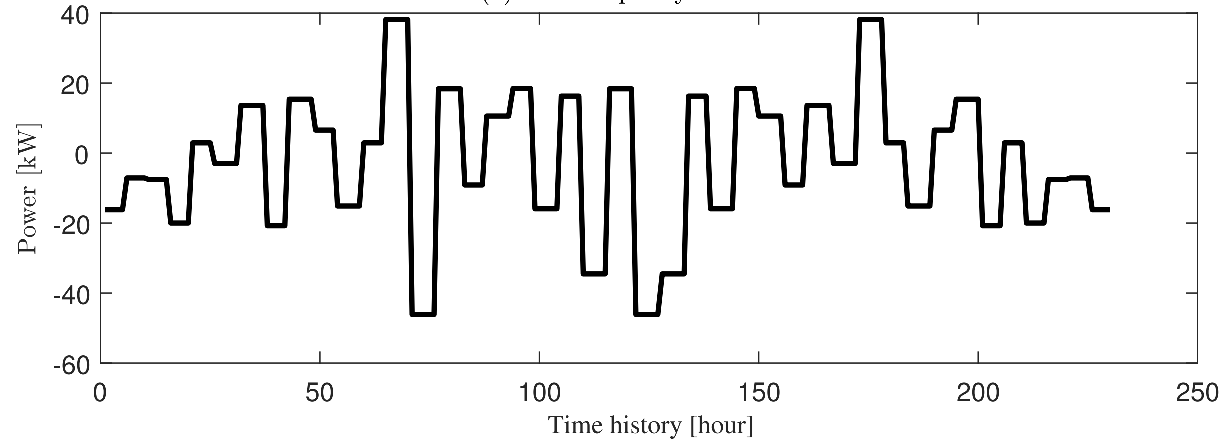
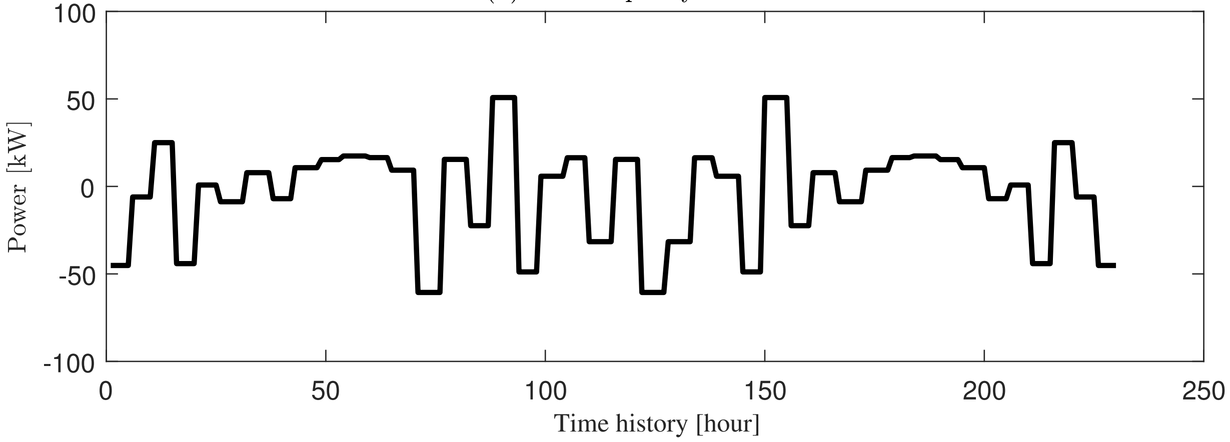


Figure 5.13: Result from optimization of fuel consumption with 21 variables during the benchmark operation in configuration 2.

(a). ESD capacity - 280 kWh



(b). ESD capacity - 400 kWh



(c). ESD capacity - 2000 kWh

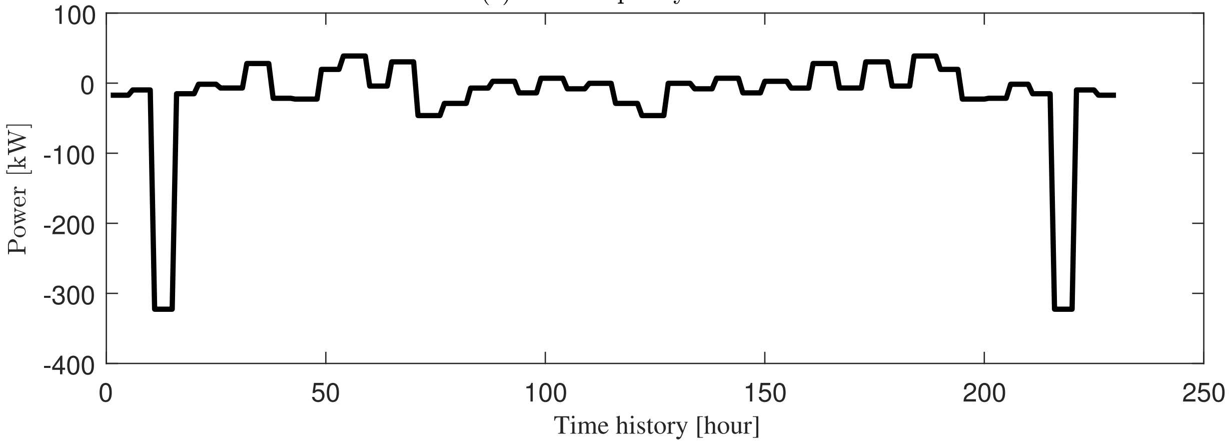


Figure 5.14: Result from optimization of fuel consumption with 21 variables during the benchmark operation in configuration 3.

Figure 5.14 (a) and (b) has more even distribution of ESD charge and discharge, while in figure 5.14 (c) there exist two discharge peak at around time instants 20 and 220 hours. This indicates large fuel saving potential during low transit operation in configuration 3, which is different from the point where largest discharge occurs. There are 30 engines rated by power 400 kW in configuration 3, which is able to run at very optimal fuel efficiency (by running less gensets) even at low load such as 9% MCR. Therefore, the largest fuel saving potential could happen on other load condition.

Table 5.13: Optimization result during the benchmark operation, method 2 with 21 variables

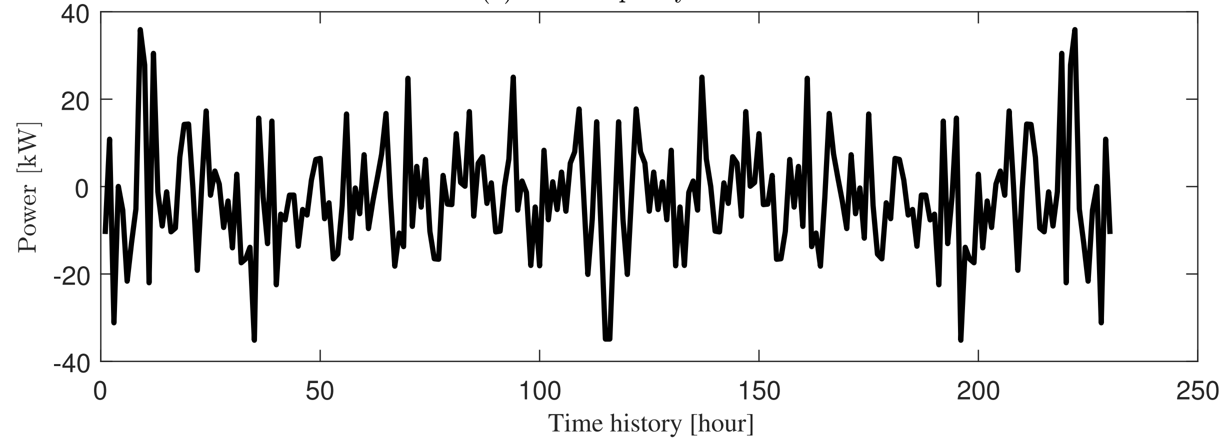
	Configuration 1	Configuration 2	Configuration 3
Total FC (Method 1) [kg]	144798	137064	153985
Method 2			
Total FC (280 kWh) [kg]	145635	138096	154937
Total FC (400 kWh) [kg]	145439	137960	154815
Total FC (2000 kWh) [kg]	144985	137458	154054
Total FC without ESD[kg]	154000	144000	165000

Table 5.13 shows the total fuel consumption during such operation without ESD and with ESD (via optimization method 1 and 2). With larger ESD energy capacity, the total fuel consumption decreases. Resulted total fuel consumption from method 2 with 21 variables is slightly higher than the one from method 1. This may be casued by not enough variables and thus it requires ESD to be charged or discharged at constant power for long duration. Therefore, optimization with a smaller time dividing and hence more variables will be presented in the following section. Besides, it also validates that configuration 2 outperform the other two configurations in terms of fuel consumption during such benchmark operation.

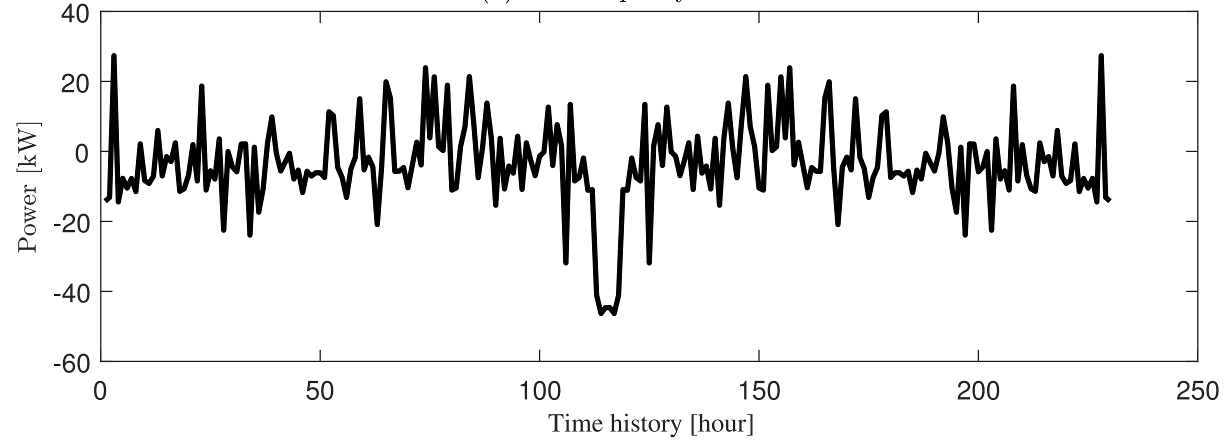
115 points

To explore what effects it will bring if we use more variables, we divided each hour into a time duration, which implies that ESD charging/discharging power at each hour is a variable. Hence, we have 115 variables in this case. Results are displayed in figures 5.15, 5.16 and 5.17 and table 5.14.

(a). ESD capacity - 280 kWh



(b). ESD capacity - 400 kWh



(c). ESD capacity - 2000 kWh

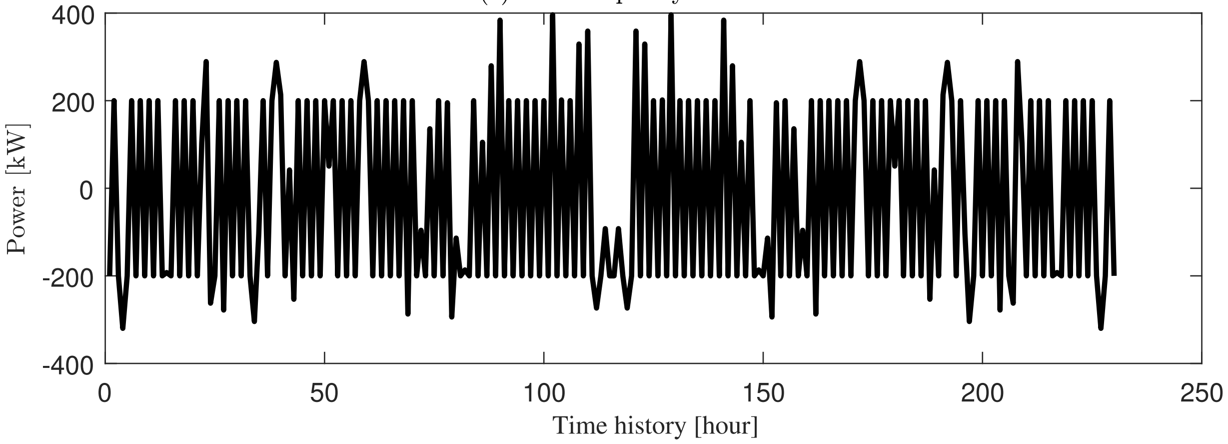
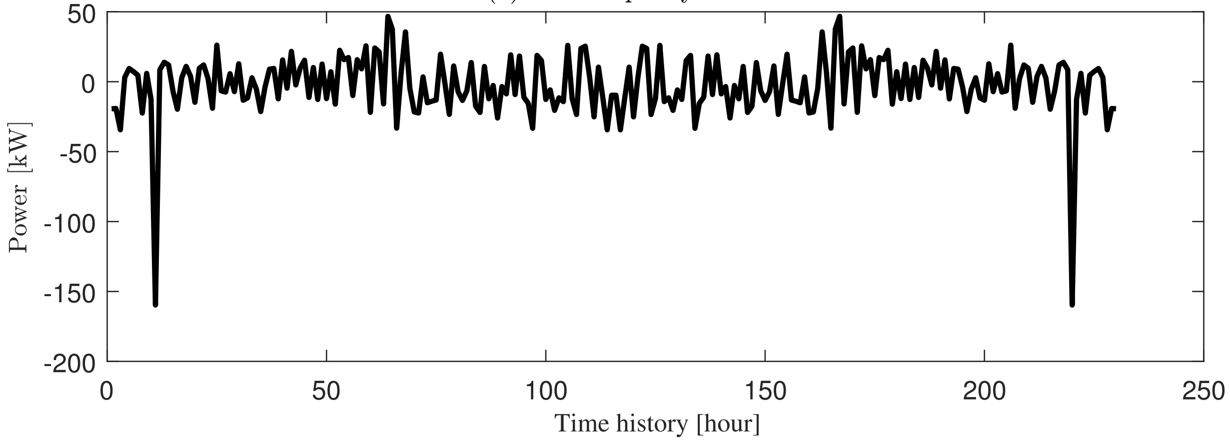
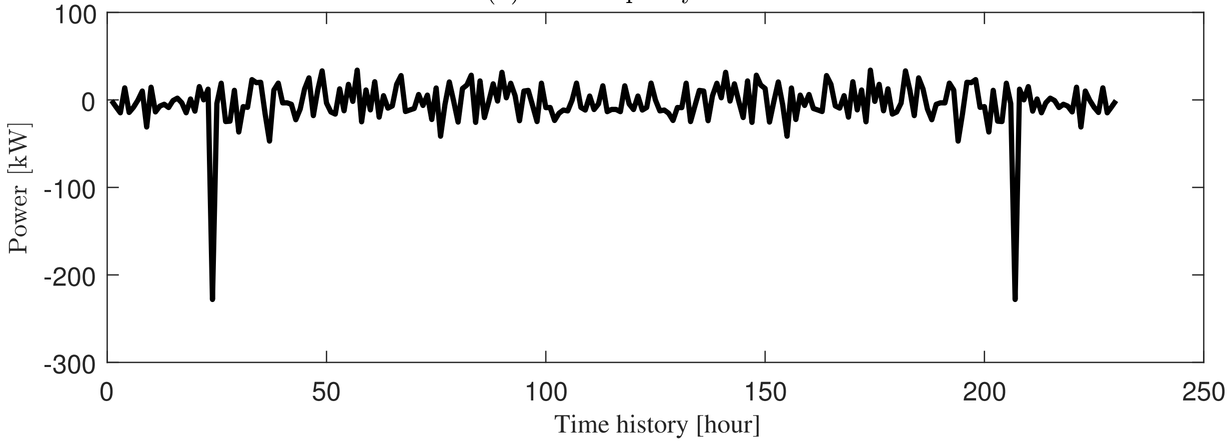


Figure 5.15: Result from optimization of fuel consumption with 115 variables during the benchmark operation in configuration 1.

(a). ESD capacity - 280 kWh



(b). ESD capacity - 400 kWh



(c). ESD capacity - 2000 kWh

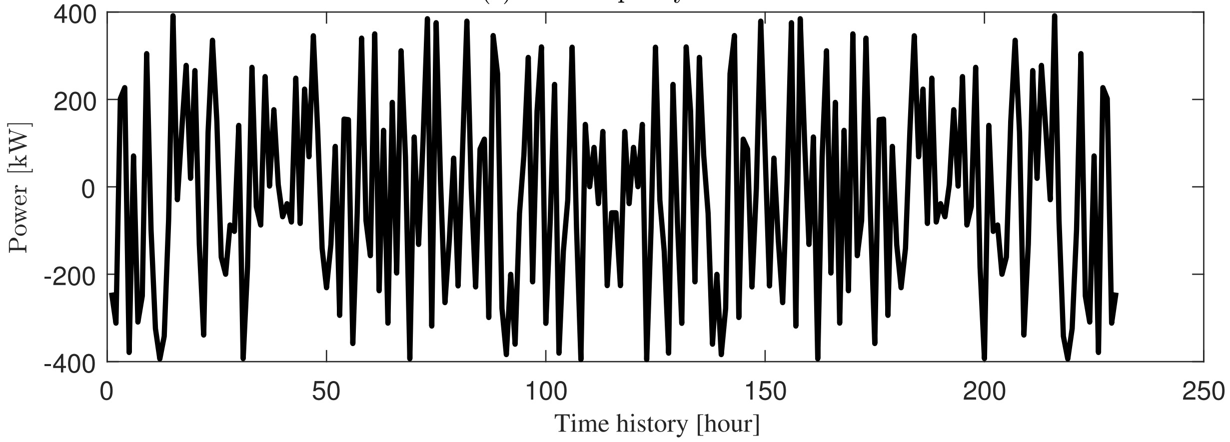
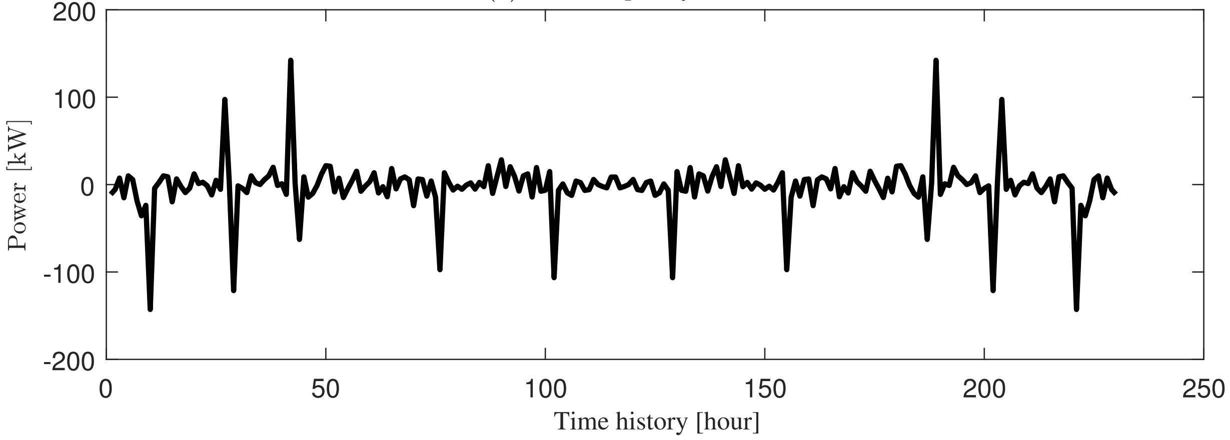
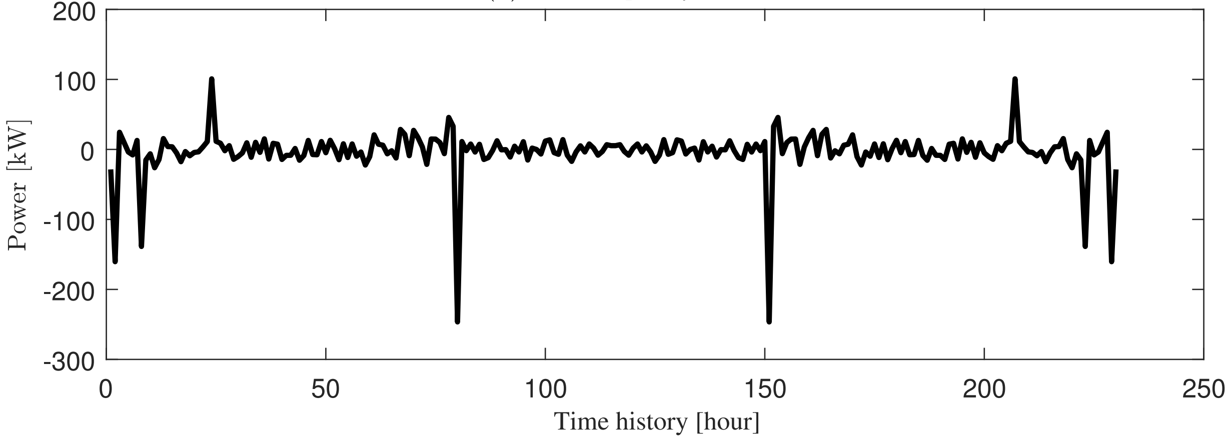


Figure 5.16: Result from optimization of fuel consumption with 115 variables during the benchmark operation in configuration 2.

(a). ESD capacity - 280 kWh



(b). ESD capacity - 400 kWh



(c). ESD capacity - 2000 kWh

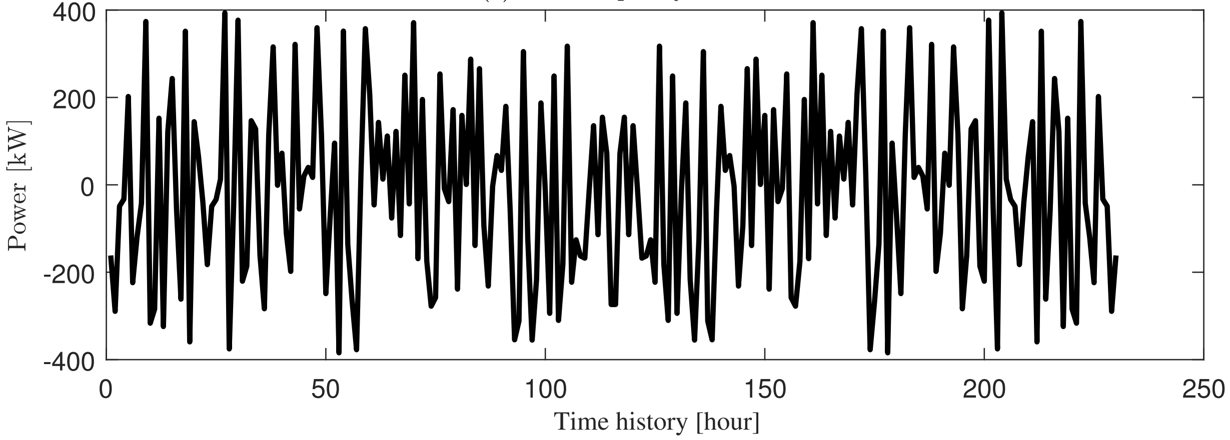


Figure 5.17: Result from optimization of fuel consumption with 115 variables during the benchmark operation in configuration 3.

From figure 5.15, more charges and discharges appear, especially when ESD energy capacity is high. Figure 5.15 (a) and (b) is very similar, despite that (b) presents a larger discharge at time instant 120 hours and lower average charge/discharge power than (a). However, with larger ESD energy capacity, both magnitude and frequency of charge and discharge increases.

The average charge/discharge power is around 200 kW, which in our case can at most last for ten hours. This may explain why the frequency of charge and discharge is very high. Besides, the peak charge/discharge power approaches 400 kW. It is not realistic to have very frequent charge/discharge at high power in practice, as high charging/discharging power influence the lifetime and efficiency of ESD.

In configuration 2, figure 5.16 presents more charge and discharge with 115 variables and there exists two main discharges in figure 5.16 (a) and (b). Figure 5.16 illustrates less regular charge and discharge where peak charge/discharge power is 400 kW.

In configuration 3, there are more significant charge and discharge during the operation with smaller ESD energy capacity, as what is depicted in figure 5.17 (a) and 5.17 (b). With a larger energy capacity, there is frequent charge and discharge with higher magnitude, which is the same situation as in configuration 1 and 2. This may be caused by the fact that it is fuel economy to discharge, which in return lead to many charges. Besides, with larger ESD capacity, in theory it is possible to charge and discharge ESD at its maximum power frequently. However, this is not preferred in practice. Therefore, more constraints can be set to decrease the frequent charge/discharge at high ESD power which only lead to little fuel consumption improvement. Compare the results from table 5.14 and 5.12, it can be told that the fuel consumption reduces even more with more variables when method 2 is applied. The results from method 1 and 2 also converges, despite that fuel consumption from method 2 is slightly lower than result from method 1. Before ESD is used for such operation, total fuel consumption in configuration 1 and 3 is 6.5% and 12.7% higher than total fuel consumption in configuration 2. After integrating ESD, the total fuel consumption difference between configuration 2 and 1 is 4.9%, while 10.9% between configuration 2 and 3. It indicates that total fuel consumption difference between configuration 2 and configuration 1 and 3 is decreased, as the improvement potential in configuration 1 and 3 is larger than one in configuration 2. However, the fuel consumption during such operation is clearly lower in configuration 2 than configuration 1 and 3, despite the larger potential of improvement which ESD brings to configuration 1 and 3.

Table 5.14: Optimization result during an operation, method 2 with 115 variables

	Configuration 1	Configuration 2	Configuration 3
Total FC (Method 1) [kg]	144798	137064	153985
Method 2			
Total FC (280 kWh) [kg]	144200	137330	154281
Total FC (400 kWh) [kg]	144144	137292	154224
Total FC (2000 kWh) [kg]	144062	136962	153746
Total FC without ESD[kg]	154000	144000	165000

Chapter 6

Discussion and Recommendations for future work

In this chapter, recommendations for improvements of the comparison study using optimization methods are given.

From the case study it is clear that the genetic algorithm works well to search for optimal operational condition for a power plant, as long as engine fuel consumption map and NOx map can be provided.

6.1 Tuning genetic algorithm parameters

As what has been discussed in section 3.1, the quality of the solution found, or the computational resources required to find it, depends on the selection of the GA's characteristics.

First of all, it is common to choose a population size between 30 and 300 for a problem contains less than thousands parameters. However, there is no thumb rules for deciding how much population size for different problem. The preferable way to choose population size is test and trial, that is, try different numbers and see if there is a clear distinction between and improvements in results. If a population size starts to give converging results, it is a good candidate. The same method works to select maximum iterations.

Population size and number of iterations are the two most important parameters in the studied optimization problems. Increasing these parameters generally lead to a better optimization result and prevent premature convergence, at a cost of longer computation time. In particular, it does not necessarily lead to a better result when these parameters are too large.

6.2 Increase sampled points in linear interpolation

Linear interpolations on both fuel consumption map and NOx emission map have been used to allow the optimization algorithm to search the optimum. The main advantage of this method is that it will have infinite computing time, being promising for real-time applications. The drawback is that the optimum will be located in the sampled points. Therefore, the amount of sampled points influences the optimization quality greatly. The values between sampled data will be disregarded, which possibly leads to a local minimum instead of an actual global minimum.

6.3 Include efficiency degradation for more component

The results from section 5.3 have illustrated that large-power engine will experience a significant efficiency degradation when the power plant operating at low load. The efficiency degradation at low load is not limited to AC/DC power converter, but also many other components such as generator, transformer and frequency converter.

6.4 More operational profiles

The comparison of results in 5.6 has shown the benefit low-power engine configuration can bring over high-power engine configuration where the engines are of same characteristic. However, the optimum solution applies only under certain operational profile instead of a generic case.

The methods can be applied to more operational profiles of an offshore construction vessel, thus leading to a more generic conclusion for guiding design of such type of veseel.

6.5 Include penalty for power transient

In this study, only average (static) power demand is considered and studied. In marine operations, transient loads appear often and can be categorized into slowly varying load and wave load. Comparing cases under average load with cases under cyclic load fluctuations which has the same average value, one will find that fuel consumption and emissions is higher in the latter cases. This is usually caused by turbocharger lag, where fuel injection changes rapidly due to load fluctuation but change in air flow does not follow the same rate. Turbo-lag influences the fuel consumption and emissions in a high-power engine and low-power engine differently due to generally different turbocharger size and delay in the air flow change. Typically, high-power engine is expected to have higher extra fuel consumption and emissions due to power transients.

Therefore, it is preferable to include penalty on fuel consumption and emissions for power transients. The penalty should be different on high-power engines and low-power engines.

On ther other side, it should be also noticed that ESD reduces transient loads on diesel engines via strategy such as peak shaving.

Chapter 7

Conclusion

In this thesis, optimization based on genetic algorithm and ESD usage method to find optimal operating point for gensets under different power demands has been explored. The optimization includes single objective and multi-objective, with regard to minimize fuel consumption and NOx emission. Optimization was achieved by applying mentioned methods finding optimum on specific fuel consumption and specific NOx map which are linear-interpolated. Operating constraints were set such that engine operates in a operational area with proper speed and torque at certain load. Besides, power constraints were set such enough power will be delivered.

An offshore construction vessel was selected, with certain power capacity requirement. Three different power plant configurations were specified for a such vessel, 1) configuration with high-power engines; 2) configuration with low-power engines which has same characteristics as engines in 1); 3) configuration with low-power engines which has different characteristic from engines in configuration 1) and 2). All configurations wew equipped with equally-sized engines, which summing up to the required capacity.

Optimization simulations were accomplished in Matlab. A typical power demand stepwise from 10% to 100% MCR has been tested in all configurations, and results have illustrated good fuel economy in configuration 2 (10.2% lower at 20% load) over configuration 1. Fuel consumption was also high in configuration 3, however, it was caused by its higher optimum specific fuel consumption feature. Monte Carlo method was applied to test the sensitivity of cost function with slightly varying optimum engine operating points for one case, where it gave consistent fuel consumption and has shown the validity of optimization results. It is recommended to integrate Monte Carlo simulation in the optimization simulation as a method to test if a global optimum can be put into realistic engineering practice. Considering AC/DC converter efficiency degrades especially at low load percentage, a study has shown that fuel efficiency is even better (15.5% lower at 20% MCR) in configuration 2 than one in configuration 1.

Multi-objective simulations on configuration 2 was presented with 3 different load condition, 20%, 45% and 70%. It illustrates different shape of pareto front, which is a group of non-dominating optimums. Generally, it showed that in order to reduce the NOx emission, fuel consumption is required to be compromised. Due to the limitation of accessible specific NOx map, limited case study was accomplished. However, the same optimization method can apply to these maps when it is accessible.

Optimization of fuel consumption with regard to minimize fuel consumption with ESD was also presented. Results have shown that by integrating ESD in the configurations, it allowed gensets to run at very optimal specific fuel consumption, especially in configuration 2 and 3. Reverse spinning and strategic loading have been discussed, which have been shown higher fuel saving can be achieved by reverse spinning in configuration 1. A benchmark operational profile have been proposed while simulations were run with two methods to reduce total fuel consumption by charging and discharging ESD at its optimum. The results have shown by integrating ESD led to fuel consumption by 5.9%, 4.8% and 6.7% in configuration 1, 2 and 3 respectively. Furthermore, configuration 1 has shown a lower fuel consumption by 6.5% and 12.7% before using ESD, and 4.9%, while 10.9% after integrating ESD during a certain operational profile.

Recommendations for further improvements are discussed in 6. In general, its is recommended to consider more realistic configurations if with more accessible engine specific fuel consumption and NOx emission maps. This will give a more reasonable comparison between configurations with low-power engines and high-power engines.

Regarding to optimization problem, it would be preferable to set more realistic constraints, especially when it relates to charging/discharging of ESD. Penalty on fuel consumption and emissions should be included where there is transient power. More optimization objectives such as minimizing capital cost and maintenance cost can be included, so that it will be a more all-around optimization problem which could be used at power system design stage in practice.

List of Symbols

ω = Rotational speed of engine

T = Engine torque

F = Fuel consumption cost function

N = NOx emission cost function

P = Engine power

P_L = Load power

P_{ESD} = ESD charge/discharge power

P_G = Power output from generator

E_C = Energy charged and stored in an ESD

E_D = Energy delivered by an ESD

P_{GC} = Power produced by a generator while charging an ESD

P_{GD} = Power produced by a generator while an ESD assist to deliver power

η_C = ESD charging efficiency

η_D = ESD discharging efficiency

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Appendix A

Engine specific fuel map

Figure A.3 shows the SFC curve of Rolls Royce Bergen B32:40 against cylinder power and speed; Figure A.1 and A.2 depicts the SFC and SNOx curve of Perkins 2506C against engine power and speed.

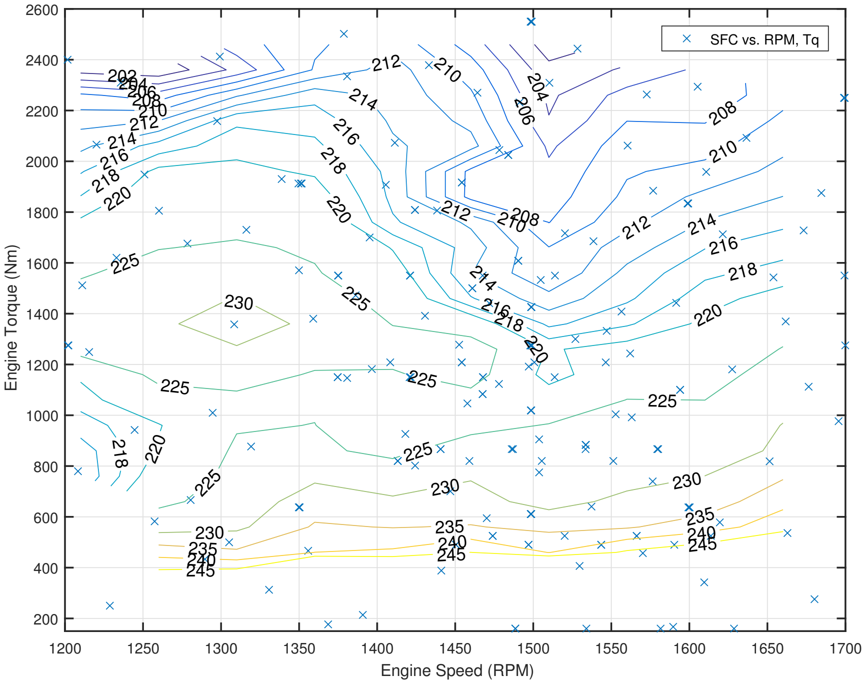

Figure A.1: SFC map of Perkins 2506C.

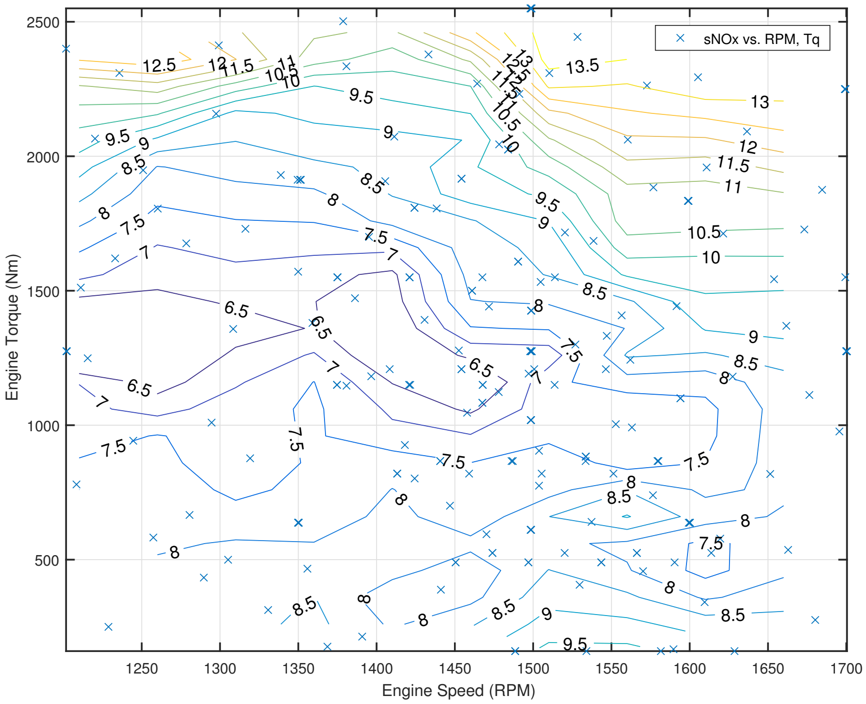

Figure A.2: SNOx map of Perkins 2506C.

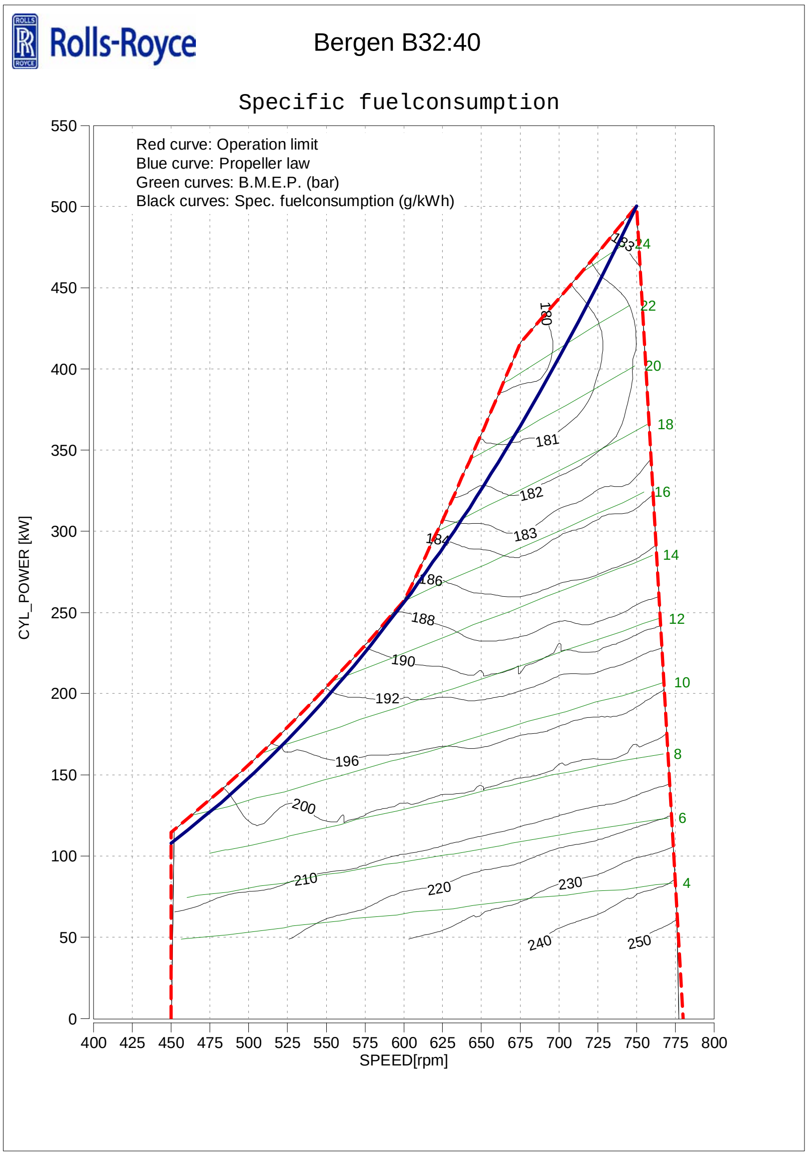

Figure A.3: SFC map of Rolls Royce Bergen B32:40. Source: Osen (2016).

Appendix B

Multi-objective optimization results at load 10% to 60%

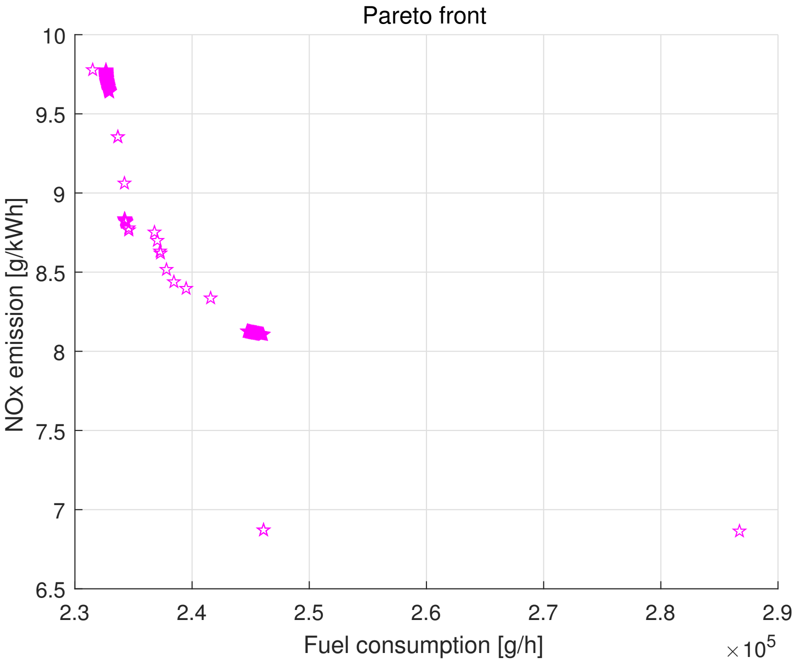

Figure B.1: 10% load

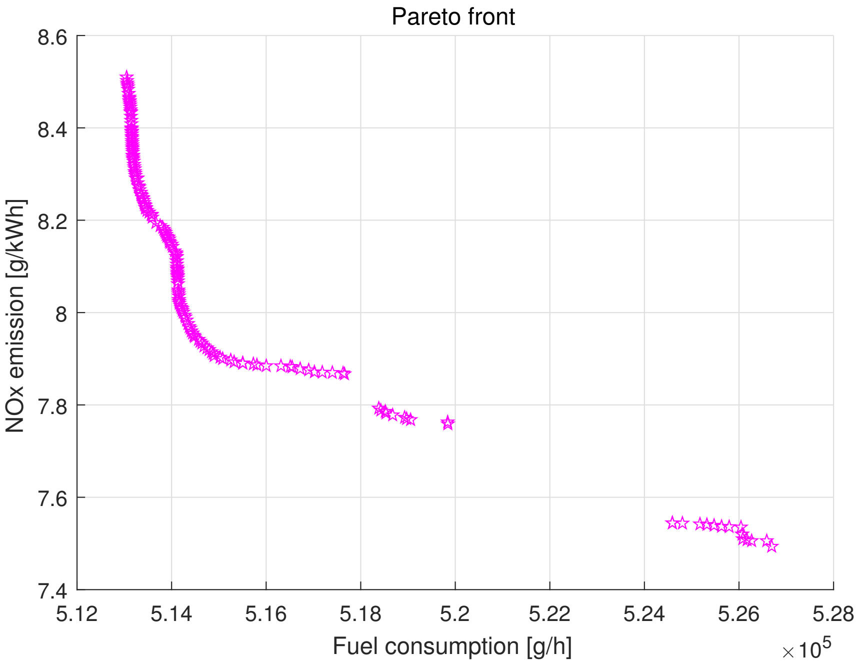

Figure B.2: 20% load

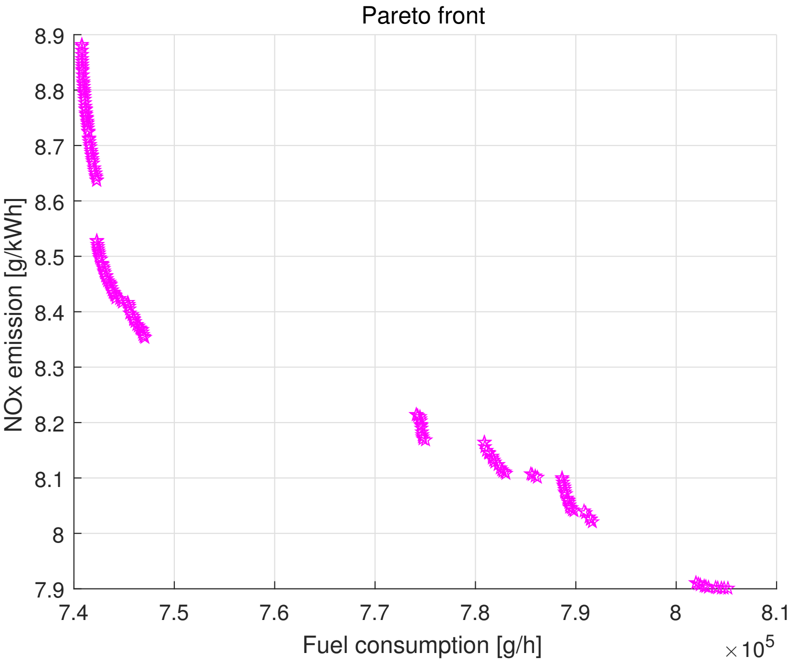

Figure B.3: 30% load

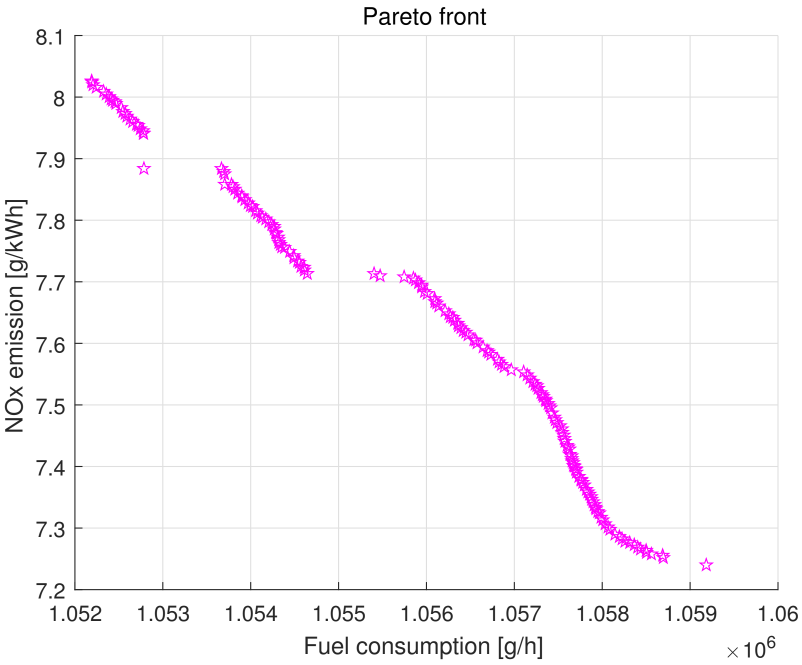

Figure B.4: 40% load

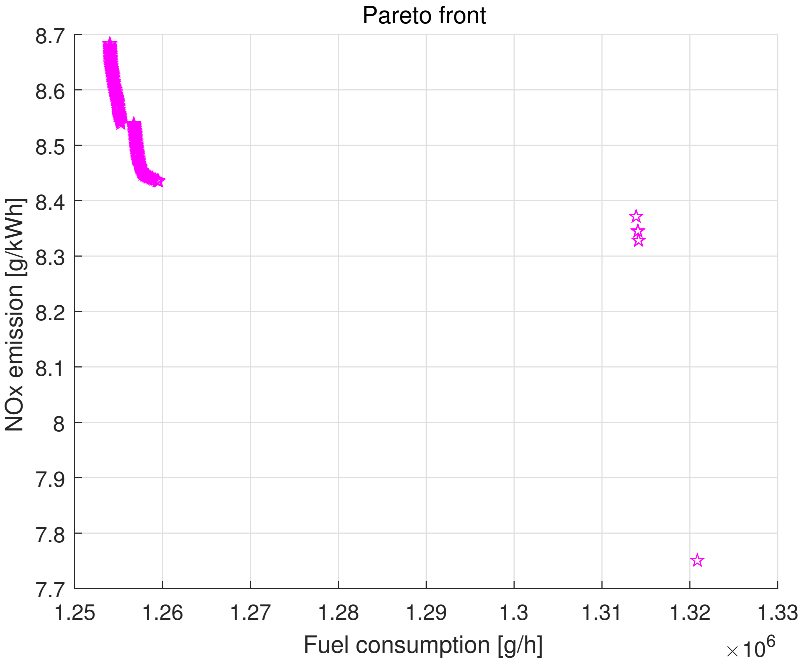

Figure B.5: 50% load

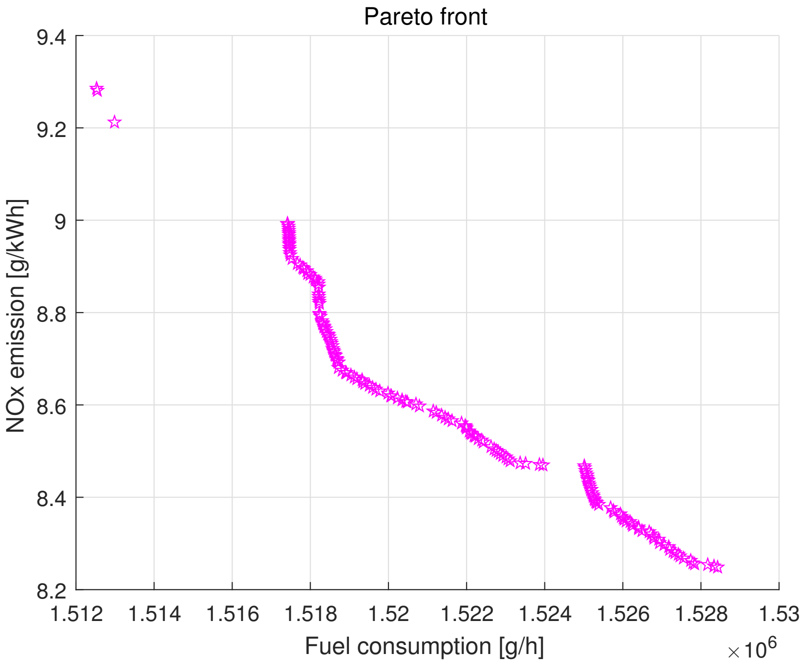

Figure B.6: 60% load