# Integration of natural gas dual fuel engines with energy storage for hybrid system in offshore DP3 vessels

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# INTEGRATION OF NATURAL GAS DUAL FUEL ENGINES WITH ENERGY STORAGE FOR HYBRID SYSTEM IN OFFSHORE DP3 VESSELS

By

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in partial fulfilment of the requirements for the degree of

**Master of Science**
Mechanical Engineering

at the Delft University of Technology,
to be defended publicly on September 26, 2016 at 10:30 AM

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# Abstract

With stricter laws on emissions in marine industry it has become necessary to shift to low sulphur content fuels, use of scrubbers for exhaust gas cleaning or shift to natural gas powered engines.Offshore Supply Vessel (OSV) have a combination of low loads due to DP3 requirements with peak loads due to position correction. A gas engine will work with reduced efficiencies under dynamic and low load condition.

To prevent this compromise in the working efficiency and for the standard working operation it is necessary for these gas engines to work under standard loads. This can be done by integrating gas engines with energy storage option available on board the vessel. This application of energy storage will level the dynamic loading curve ensuring the gas engine running at given standard constant load.

The goal of this thesis research is to integrate natural gas dual fuel engines with energy storage for offshore DP3 applications. To achieve this goal a dynamic simulation model will be developed for the energy storage in Matlab/Simulink which will be integrated with the available gas engine model of IHC. A comparison is be made with some key parameters being the fuel consumption, emissions, operating & installation cost and their compliance with classification society for DP3 vessels.

Gas engine model available at MTI will be made suitable for the OSV with some required changes. A Matlab/Simulink model for the chosen energy storage option from phase 2 will be a dynamic model. In the final stage this energy storage model will be integrated with the gas engine model with proper system integration. These models developed and integrated will be based on the literature study of my thesis.

# Preface

This MSc. thesis is the result of almost a year long graduation process carried out at the Technical University of Delft and IHC MTI Delft. I would like to express my thanks as below:

IHC MTI: Benny Mestmekker, for helping with my report and showing his enthusiasm for this graduation project. Furthermore all the colleagues, graduation students and other interns that made my time at MTI a very pleasant one. An extensive thank you to MTI for having me and providing all the necessary resources to complete this project successfully. I hope this thesis will help your business in the future.

TU Delft: Prof. Milinko, for his guidance and supervision during this graduation project. Prof. K. Visser, for being the committee chair and his supervision.

My parents and my sister for supporting me to be a student at TU Delft for studies. My friends for cheering and helping me when needed. Finally my girlfriend who helped me right from getting up in the morning to putting my full efforts in the project.

Vivek Varia
Delft, September 26, 2016

# Contents

# 1
# Introduction

New propulsion systems are designed to be accommodated in the design phase of ships with main aim to provide best efficiency with minimal fuel consumption along with complying with the classification societies and be environmental friendly till maximum extent. The efficiency of the complete vessel does is not dependent on the single component but is dependent on the synergy between those components.

The International Maritime Organization (IMO) announced that in 2015 regulation known as 'Tier III' will come into effect in emission controlled areas (ECA) and globally from the year 2020. Also from 2020 the sulphur oxide emission will be limited to 0.5 % by mass.[1] There also lies an air of stricter regulations on the emission in the near future. This regulations will have great impact on shipping industry which has large contribution of green house gas to global emission.

Generally hybrid electric propulsion system refers to diesel electric propulsion accompanied with energy storage. For a ship operator the factor contributing to the ship operation cost is the fuel cost.With stricter laws on emissions in marine industry it has become necessary to shift to low sulphur content fuels, use of scrubbers for exhaust gas cleaning or shift to natural gas powered engines. Use of low Sulphur content fuel and making use of exhaust gas treatment methods are costly leading to increased running cost of the ship. The solution of natural gas dual fuel engines is the option that comply with the emission regulation along with not being a costly option compared to other alternatives. One of the major drawback of gas engine is its poor behaviour in transient condition which is upholding for a dynamic positioning (DP) vessel thereby making use of gas engine a less preferred option for these kind of vessels. To prevent this compromise in the working efficiency and for the standard working operation it is necessary for these gas engines to work under standard loads. This can be done by integrating gas engines with energy storage option available on board the vessel. This application of energy storage will smoothen the dynamic loading curve ensuring the gas engine running at given standard constant load. In this thesis, integrated power plant concept of gas engine with energy storage will be cited as hybrid propulsion system.

## 1.1. Objective

The main objective of this research is to integrate the natural gas Dual Fuel (DF) engine with energy storage for DP class-3 offshore vessel.The objective further includes developing hybrid propulsion plants for an OSV and compare them based on fuel consumption,operating & installation cost, emissions and their compliance with classification societies.

Although the ship propulsion system includes many components, this work focuses on engine and electric machinery that is generator, motor and electric grid for power transmission. Models for other components or comparison between power configurations will not be discussed.

## 1.2. Work approach

In this thesis focus is made on main propulsion components used in hybrid propulsion system. After suitable selection of this components appropriate modelling approach is chosen to model them in MATLAB/SIMULINK. Using the existing models available from IHC and TU Delft, modifications were made to integrate them. These included modification in generator and motor model, adding power controller to the battery model and developing DC grid for the integration. After these modifications they analysed for the verification.

## 1.3. Thesis structure

The thesis work is present in following sequence in this report:

Chapter 2 gives background information about offshore vessel and its different types; and information about dynamic positioning with rules and regulation of different classification societies for the same.

Chapter 3 explains hybrid propulsion system and different layouts that can be used for offshore supply vessel. This chapter also gives information about the different parameters based on which these propulsion layouts will be compared.

Chapter 4 describes different components present in the hybrid propulsion system.

Chapter 5 describes the modelling approach of these components and their dynamic behaviour.

Chapter 6 shows results of the integrated models for different case and their comparison based on key parameters.

Chapter 7 gives conclusion and recommendation for future work.

# 2
# Background

Offshore vessel is the vessel capable of doing any operation from transport of goods to safety or rescue operation, anchor handling and many more. Based on its design it can also be used for more specific tasks like subsea exploration, post drilling operation or control and support for remotely operated vehicles (ROV).

## 2.1. Offshore vessel

OSV is general name for several different types of vessels. These vessels are designed based on their purpose and task to be performed.

### 2.1.1. Platform supply vessel

Platform supply vessel (PSV) is a type of vessel considered to be the working horse of the offshore supply vessel category of vessels. It can be used anywhere in between mainland to offshore installations. Because of their design with large open deck space in the aft side of the vessel it is used for transport of cargo. Along with transport of cargo this type of vessel can provide support to offshore platform by providing extra storage space on a temporary basis. It can be also be used for rescue and fire fighting operation. It is a DP 3 class vessel with good manoeuvrability requirement to keep the vessel at safe distance from platform during the cargo transport from the platform or to the platform.

Figure 2.1: Platform supply vessel [2]

### 2.1.2. Multi-purpose support vessel

This is complex and sophisticated type of vessel designed to perform various subsea operations. It is generally large and costly compared to other offshore vessel. This type of vessel is used for operations like subsea construction, ROV supports and pipe handling. This vessel can also be designed for specific purposes depending upon the equipment installed on-board. This vessels require high electrical power because of the heavy on-board machinery.

### 2.1.3. Anchor handling vessel

Anchor handling vessel (AHV) similar to PSV have large open deck in the aft side of the vessel. This vessel is used to perform operations like lifting and setting of anchors, towing offshore units thus requiring powerful winches and cranes. This reduces the open deck space with limited space left for transport of cargo. It is a DP 3 class vessel also used for performing fire fighting operations or as an oil spill recovery unit. Because of heavy lifting operation and high bollard pull requirement for handling of anchors and towing operation this vessel requires powerful prime movers.

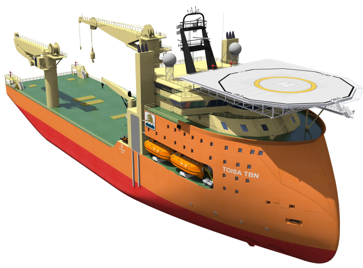


Figure 2.2: Multi purpose support vessel [3]

Figure 2.3: Anchor handling vessel [2]

Table 2.1: Different offshore supply vessels

| | |
|---|---|
| Platform Supply Vessel | Transport of cargo and crew<br>Rescue operation<br>Platform support |
| Multi-purpose Service Vessel | Cable handling<br>Construction<br>Post drilling operation<br>Transport function<br>Subsea exploration and support<br>Flexible pipe laying operation |
| Anchor Handling Vessel | Anchor handling<br>Rescue operation/standby<br>ROV<br>Towing<br>Platform Support |

### 2.1.4. Current propulsion system

The proposed benchmark diesel electric propulsion proposed by ABB and MAN in their report for an offshore supply vessel can be shown in figure 2.4 with four diesel generators and DC grid of 4160V.

## 2.2. Dynamic positioning

A DP vessel has remain stable over a certain region in the sea or in relation to another vessel or offshore structure. Conventional mooring cannot be used during this time as it is not desirable as any fault in mooring system may cause mishap which allows free movement of vessel in some direction which is not intended for this operation.

In the DP mode all the thrusters are working to keep the vessel steady at the correct position irrespective of weather conditions. The power consumption in this operation may vary drastically from 10% of the total installed power to 30% in rough weather conditions. There are cases where at a certain instance of time the load transition may be as high as 30-40%. There may be chances where the thrusters or the propellers may

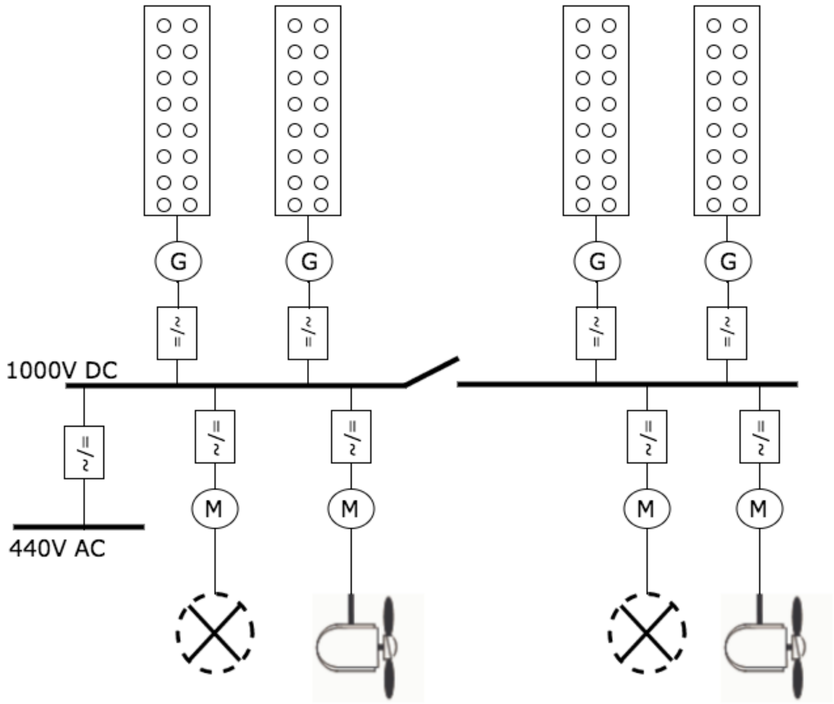



Figure 2.4: Standard Electric Propulsion with DC grid

come in free air under DP mode because of the rough weather and heavy tides in the sea, resulting in maximum possible load variation for the propulsion system.

Under DP mode a vessel operating near offshore structure must be capable of moving to a safe distance under emergency situations as well establish full power in under one minute of operation.

The DP system has to measure the current position and the heading position of the ship. As dynamic positioning works on the information of multiple devices which collect different data on-board the ship. Most commonly used methods are satellite navigation system (Global positioning system (GPS) and Differential global positioning system (DGPS)), mechanical reference system, hydro acoustic position reference system and heading reference system (gyrocompass). More accuracy is achieved by combining more methods. [4]

### 2.2.1. DP guidelines and requirements for redundancy

Equipment's used to for positioning the vessel should be robust and reliable required for the safe offshore supply vessel operations. Most of the offshore supple vessel are equipped with the DP systems. All the DP vessels designed, constructed and operated must follow the internationally developed and recognized rules and regulations. These includes IMO MSC circular 654 (Circ.645), titles "Guidelines for Vessels with Dynamic Positioning Systems". All the rules and guidelines for DP vessels are focused mainly on the construction and operation with the prime objective of redundancy and creating a hierarchy of equipment's used for DP operation.

#### Failure modes for DP3

The loss of position shall not occur for in case of single component or compartment failure. The single component failure includes failure of an active or static component.Single component failure includes:

- Active component or system
- Static components as specified in the rules
- Other static components which are not properly documented with respect to protection
- A single inadvertent act of operation. If such an act is reasonably probable

- Systematic failures or faults that can be hidden until a new fault appears
- Automatic interventions caused by external events, when found relevant (e.g. automatic action upon detection of gas).

Following components are included in single failure:

- Coolers
- Filters
- Motorised valves
- Fuel oil service tanks and appurtenant piping supplying the engine(s)
- Electrical and electronic equipment (this includes all on-board equipment and systems, e.g. any safety shut-down systems, vessel control systems, etc)
- When considering single failures of switchboards, the possibility of short-circuit of the bus-bars has to be considered

In addition to the above mentioned single failure modes failure mode also includes: loss of all components in any watertight compartment, from fire and flooding; loss of all components in any one fire-subdivision, from fire or flooding

### 2.2.2. IMO guidelines

"Guidelines for Vessels with Dynamic Positioning" provides an approach of achieving the acceptable reliability standard for the position keeping. There are three equipment class based on redundancy allowing the ship owner to select an appropriate class of vessel matching its operation. The three classes are described below [5]:

- Equipment Class 1: Loss of position may occur in the event of single fault
- Equipment Class 2: Loss of position should not occur in the event of a single fault in any active component or system (e.g. generators, switchboards, valves, thrusters, etc. ). Static components will not be considered to fail where adequate protection from damage is demonstrated. Loss of position under this class may include loss of any static equipment like the cables, pipes, manually operated valves etc.
- Equipment Class 3: There should be no loss of position under failure of an active or static equipment in the system. Inadvertent situations like the fire or flooding in one the compartments are also included in the failures due to which there should be no loss of position.

Table 2.2: DP Class overview

| | **IMO** | Corresponding Class notation | | |
|---|---|---|---|---|
| | DP Class | **American Bureau of Shipping (ABS)** | **Lloyd's Register** | **Det Norske Veritas (DNV)** |
| Manual position control and automatic heading control under specified maximum environmental conditions | - | DPS-0 | DP(CM) | DPS 0 DYNPOS-AUTS |
| Automatic and manual position and heading control under specified maximum environmental condition | Class 1 | DPS-1 | DP(AM) | DPS 1 DYNPOS-AUT |
| Automatic and manual position and heading control under specified maximum environmental conditions, during and following any single fault excluding loss of a compartment computer systems | Class 2 | DPS-2 | DP(AA) | DPS DYNPOS-AUTR |
| Automatic and manual position and heading control under specified maximum environmental conditions, during and following any single fault including loss of a compartment due to fire or flood. | Class 3 | DPS-3 | DP(AAA) | DPS 3 DYNPOS -AUTRO |

## 2.3. Guidelines for gas fuelled dual fuel engines

Firstly the gas fuelled engines should be able to comply with the class rules regarding the design, which is not separately mentioned for gas fuelled engines. Further the gas engines should be able to comply with the class requirements for transient load response, load steps and rated loads with minimum frequency drop and least recovery time for the stable operation. [6]

- Currently there are no mandatory safety regulations specifically available for marine gas engines. But IMO is currently developing International Gas Fuel Code (IGF) based on the Interim Guidelines MSC.285(86) of 2009. There are plans to implement these regulations by 2017.
- Many internationally recognised classification societies have issued their specific rules for gas fuelled engines for avoiding the danger of explosion, redundancy for propulsion and gas leakage safety.
- In case of shut down of gas supply system a principle favouring to DF engines has been designed with gas and liquid fuelled engines in order to supply unaffected power supply under such shut down operation.
- For achieving the redundancy and depending on the class requirements engines must be placed in two separate engine rooms with separate gas supply or supply means of back up propulsion by using DF engines or energy storage. There is another option to use two separate gas feed system from one Liquified natural gas (LNG) tank which by itself must follow strict restrictions.
- There should be advanced misfire and knock detection system installed to bring the engines into safe operation (load reduction or shut down) under such situations.
- Regarding the LNG storage tanks generally type C tanks are used. The reason being their availability, flexibility of installation. Depending on class requirements for DF engines one or more LNG tanks should be used with separate gas feed systems. Separate class requirements for gas storage and types of tanks is also being developed.
- Regarding the emission gas fuelled ships are most promising options with IMO Tier III regulations. Not all marine gas engines are covered under IMO emission limits yet. While design phase the situation of methane slip has to be considered for the operation area of the ship and local emission laws.
- The logistics of LNG fuel and its safety is also very important. A normal LNG terminal is suitable as a bunkering station for general LNG fuelled ships. International Organization of Standardization (ISO) is currently working on standardization of bunkering equipments like house, couplings and many more with an aim to be inducted in IMO IGF code.

#### Explosion Prevention / Engine room ventilation

This is very important topic for safety regulation which puts down specific requirements on venting of engine rooms, air exchange per hour, number of gas detectors in engine rooms and tank room and many more.

- Gas engines rooms should have double walled gas feed pipes with proper ventilation space between the inner and outer pipes with gas detection system installed. Other alternative way is to place the gas engines in two separate gas tight engine rooms with separate gas feed system for individual rooms. This rooms should have pressure relief valves and escape ducting. This concept is referred to as Gas safe machinery space.
- In the situation of gas leakage the engine compartment, the complete compartment should shut down and vented to a safe area. Each of these compartment is seen as a 'Safeguard' or 'Emergency Shut-down (ESD)' protected area machinery.

#### Guidelines for batteries used as energy storage ships

The class rules covers the use of batteries as a part of the propulsion energy for vessels either for hybrid solution or full battery powered vessels. The rules are developed by DNV battery power rules, 2012. The main rules includes:

- Specific requirements for fire and safety of battery
- Specific requirements of battery spaces
- Environmental control of battery spaces
- Rules for using battery for DP operation

### Safety notation

There are separate rules for using battery as auxiliary power source and when used as the main propulsion power source. Here are some of the main safety rules regarding use of battery for both the operation:

- The battery space should not contain redundant propulsion or steering systems
- The battery room should have safety assessment for gas development(flammable and corrosive), fire risk, explosion risk with necessary alarm systems for gas detection, ventilation and loss of propulsion or auxiliary for essential services
- The energy management system installed should control the battery temperature by limiting the charge and discharge current or limiting the battery voltage. It should also monitor the energy capacity of batteries, time range for which the battery can supply energy for the given operation and give alarms for critical conditions.

### Design principles for battery power system

When battery is the main source of power or one of the propulsion power source it shall contain minimum of two independent battery systems installed in two separate battery rooms. Cable routing should be done with short circuit capacity with sufficient breakers and fuses for local operation.

### Battery system certification

The certified battery system includes following main components:

- System design
- Safety description
- Integrated battery management system (BMS) which controls and monitors battery conditions and gives alarms for any abnormal condition.
- Independent emergency disconnect
- Class dependent safety and redundancy

# 3
# Concept Design

This chapter discusses about hybrid propulsion system and its advantages over standard propulsion system. It also describes different types of power train concepts with energy storage, that can be used for DP3 class vessels. The chapter concludes with details about the performance indices on which different propulsion system will be compared.

## 3.1. Power train design

The power train concept design includes following steps:

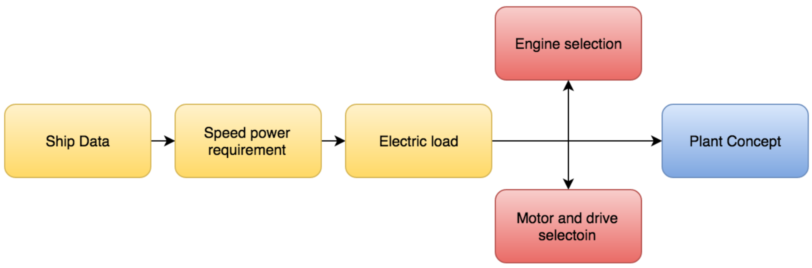



Figure 3.1: Steps involved in power train design

The vessel type and its load requirements has strong influence on the propulsion plant design. This thesis is focused on the power train configuration for DP3 vessel in particular. The hull shape analysis and fouling are out of the scope of this thesis. The concept is designed on basis of reducing the fuel consumption of main engines.

## 3.2. Electric propulsion

Electric propulsion is a solution mainly used in special ice going vessels, passenger vessels or vessels powered by LNG. Electric propulsion is arrangement of marine propulsion with gas turbines or an engine with generator that produce electricity which is used to power the electric motors. This system reduces the need of gearboxes by using electric transmission rather than using mechanical transmission. Using electrical propulsion has many advantages like freedom of engine room placement, acoustic decoupling of engine room from the hull of the ship to make it less noisy and significant weight reduction [7]. Electrical propulsion is getting more popular because of the ease to use in variable loading condition requiring variable power.

## 3.3. Hybrid propulsion

Hybrid propulsion is a propulsion arrangement where electric system of mechanical drive is implemented with energy storage system whether in series or parallel. In marine propulsion hybrid propulsion describes a propulsion line where the mechanical prime mover in the main driver for driving the propeller with an electrical driven motor to be used in low load condition for high efficiency and redundancy. In hybrid system the vessel can achieve propulsion from fuelled power source (e.g. natural gas engine) or through an energy source (e.g. energy storage device). [8]

### 3.3.1. Operation of hybrid propulsion

Hybrid propulsion works on the principle of energy buffering. In this propulsion higher power is extracted from engine then the power required for propulsion. The excess energy can be stored in energy storage (e.g. charging the batteries). When the energy storage are full, engines can be turned off and low propulsion power can be supplied by the energy storage. When the energy storage are depleted the engines are again turned on, which will work on higher loads by providing power for propulsion as well as the charging the energy storage. The engine is thus working at higher loads, resulting in higher efficiency. This is achieved by selecting engine sizes that operates at optimal loads, with additional power requirement being fulfilled by the energy storage.[9]

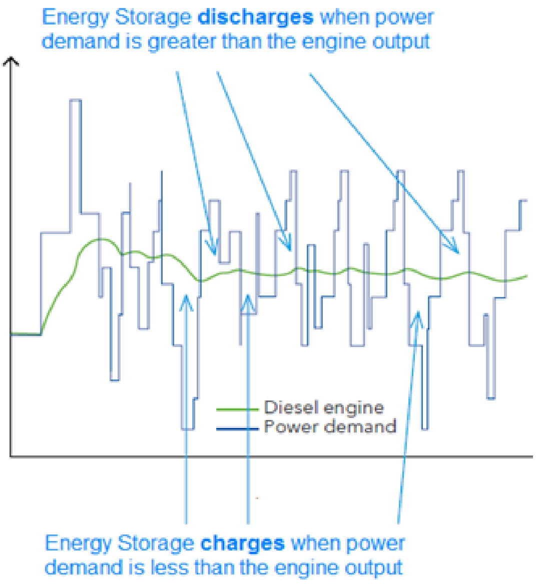



Figure 3.2: Charging and discharging of energy storage during operation

Advantages of using hybrid system in ships:

- Running engines at optimum loads.
- Reduce emissions: In areas with strict emission laws hybrid system can use the power from energy storage devices with sufficient capacity making the operation emission free.
- Power redundancy: All DP vessels have redundancy requirements in the machinery system. In case of failure of some parts of the system, there should be sufficient power to operate the vessel. This makes running more prime movers than needed to deliver the required power ensuring satisfactory redundancy. This makes the engine to operate at low loads making them inefficient and produce high emissions. On a longer course of time this type of operation may cause mechanical wear of the engine. Energy storage device in this case can provide required power for given amount of time to complete the operation safely there by increasing the redundancy. This can result in reduction of number of engine running at a given time which leads to a reduction in fuel consumption, emissions and maintenance cost.
- Transient load response: Prime movers have limited load response capability. As discussed earlier the engines ability to transient loads depend on various factors like the type of fuel, quality of fuel, combustion cycle, geometry and size of turbocharger. By integrating the engine with an energy storage device, makes engine run at constant and optimal load and letting the energy storage deal with the load variation.
- Energy harvesting and recovery: There are other potential energy sources on-board for the energy harvesting like the solar cells. If there are cranes on-board, the use of regenerative braking inside the winches can produce electrical power. Moreover energy recovery form the propeller, damping the motion during ships deceleration energy can be recovered which can be further stored into this energy storage devices. Waste heat recovery system is also efficient in hybrid system.

- Noise and vibration are another form of pollution which can be reduced by using hybrid system. This is desirable for the comfort and working environment for the crew. In passenger vessel this issue is of prime importance for the passengers comfort.

### 3.3.2. Classification of hybrid ships

- Full electric ships (FES): These are ships with all power for propulsion and the auxiliaries is supplied by the batteries on-board the ship.

- Hybrid Ships (HES): A hybrid ship uses energy storage to increase the engine performance but unlike plug in hybrid ships it cannot use the shore power to charge the energy storage devices.

- Plug-in hybrid ships (PHSE): These are hybrid ships similar to plug in hybrid vehicles which has batteries along with a conventional engine. The batteries can be charged using the shore suggesting the name of plug in hybrid ships. The ship can operate either on batteries alone during manoeuvring in port or during stand by operation depending upon the operation. [9]

Base on propulsion layout hybrid propulsion system can be classified as follows:

#### Serial hybrid

In this hybrid layout electric motor is the sole driver for driving the propeller shaft. This electric motor can be driven by engine via a generator or an energy storage. This power plant can have flexibility of using energy storage for propulsion or running without an energy storage. This power plant is capable to integrate AC or DC distribution system easily. Figure 3.3 shows a basic serial hybrid propulsion system.

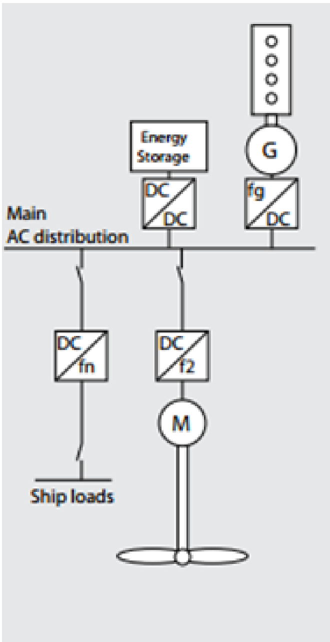



Figure 3.3: Serial hybrid propulsion with disel electric drive and energy storage [8]

#### Parallel Hybrid

In this type of propulsion the propeller shaft is driven by an engine or an electric motor or both together using a gearbox. The electric motor is further driven by an energy storage or another engine as discussed in the above section of serial hybrid propulsion. Figure 3.4 describes basic parallel hybrid propulsion system.

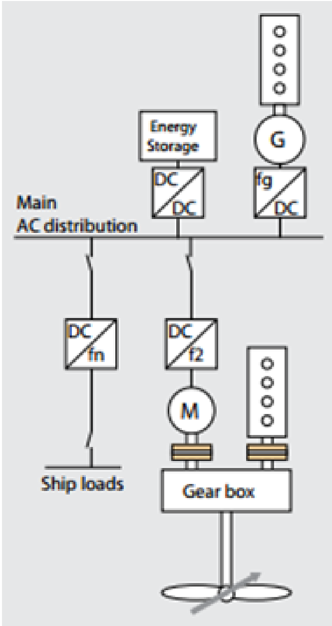



Figure 3.4: Parallel hybrid with electro mechanical drive and energy storage [8]

### 3.3.3. Comparison between parallel and serial hybrid propulsion

In serial hybrid system there are losses in electric generator, energy storage, motor controller and motor. In serial hybrid propulsion for the same power output at the propeller shaft compared to conventional direct drives it requires bigger engine to compensate for the above mentioned losses. This will result in significantly higher cost in comparison to direct drives.

Parallel hybrid are more efficient compared to serial hybrid. For parallel hybrid systems both motor and generator functionality can be combined into one unit saving weight and efficiency loss. This propulsion technique provides benefit at mid and low cruising speed. When there is need of maximum power the propeller receives power directly from the engine and the hybrid system does not play any role. Parallel hybrid is more reliable compared to serial hybrid as when electronic component breaks down, this would lead to shut down of serial hybrid. In parallel hybrid since one engine and the hybrid system are parallel any break down in electronic component would not lead to complete shut down of the propulsion unit. When electronic component are smaller and lighter then serial hybrid can prove to be more cost effective compared to parallel hybrid.[10]

## 3.4. Type of propulsion

Two different types of ships are available for analysis. One is geared drive with fixed pitch propeller; the other is with thrusters powered by electric motor.

### 3.4.1. Fixed propeller drive

This types of ships have fixed pitch propeller attached directly to the prime mover generally a diesel engine. Manoeuvring is done using the rudder by applying hydraulic pressure on the same. For the DP3 class vessel this is not the best choice because of poor behaviour to transient loading behaviour and difficulty for fast manoeuvring. The energy flow diagram of fixed pitch driven ships is given in figure 3.6. The used abbreviations are:

- ES - Energy Storage
- M - Mechanical linkage
- E - Electrical linkage
- P - Propeller

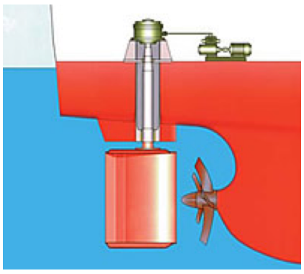


Figure 3.5: Schematic of fixed propeller drive

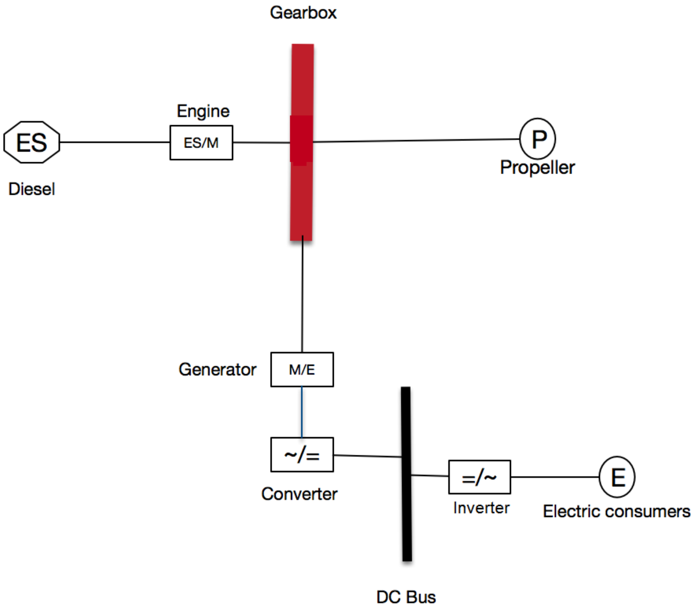



Figure 3.6: Energy flow in fixed propeller drive [11]

### 3.4.2. Azimuth thruster

The second type of ship is equipped with electric motor driven pods. The drive of pod is given in figure 3.7. They are capable of rotating in $360^o$ therefore rudder is not needed in these types of ships. This improves manoeuvring capability of the ships as well as the transient load behaviour. This makes the thruster driven ships a prime choice for DP3 vessels.

Figure 3.7: Schematic of POD drive [11]

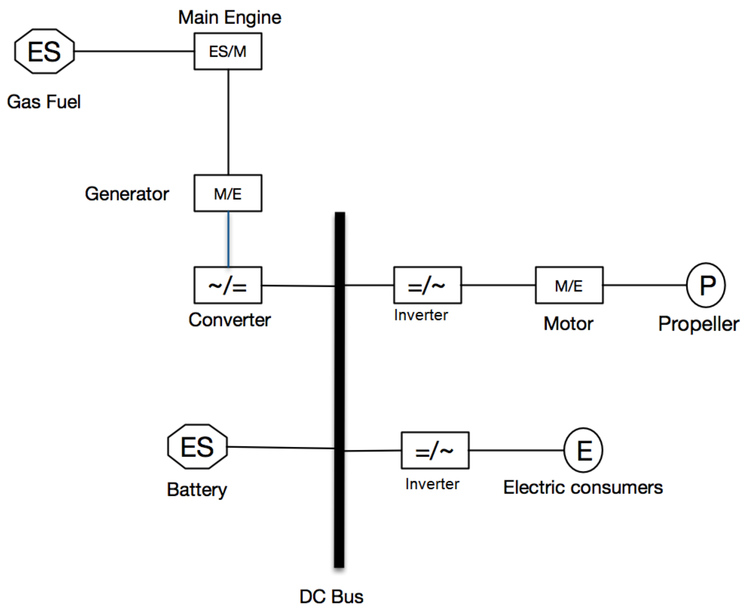



Figure 3.8: Energy flow in POD drive

## 3.5. Operation modes

A hybrid concept power train can have different operating mode with electric machine working either as generator or the motor. There are two main operation modes for a hybrid concept power train.

### 3.5.1. Power take off

Under this mode of operation main engine is driving the propeller generally via a generator attached to it through electric power generation as well as provide the auxiliary power requirement on the ship. The only prime mover under this mode is the main engine which runs on high and efficient load. Figure 3.9 shows energy flow for this mode of operation

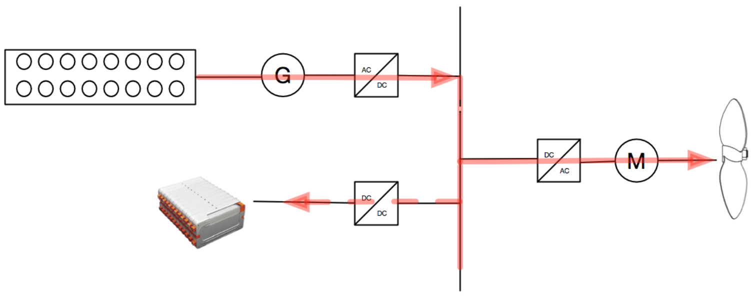



Figure 3.9: Energy flow in power take off mode

### 3.5.2. Power take in (PTI)

Under this mode of operation (PTI), electric machine or the energy storage delivers the extra power to the propeller via generator which is connected to the to the main engine through a gearbox or an electric network. For this situation instead of installing larger engines PTI mode can provide this excess power requirement via auxiliary power sources. Depending upon the operation profile the excess power requirement for short durations is provided in form of electrical power which can easily be transported through the ship.

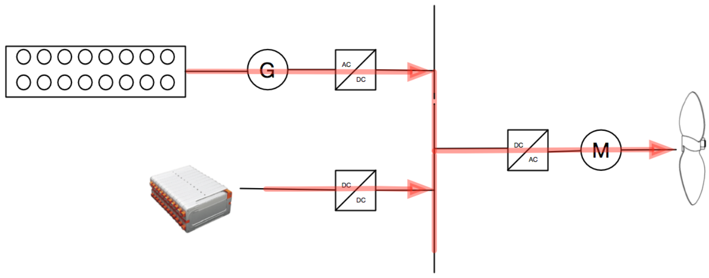



Figure 3.10: Energy flow in power take in mode

## 3.6. Detailed concept overview

This research is focused for DP3 class offshore supply vessel. As discussed in section 2.2 because of the class requirement a DP3 class vessel should be able to generate full power under single failure or loss of compartment for the station keeping operation. This requires redundant system to be installed on-board. Along with redundancy class requires minimum two separate engine rooms that is able to produce full power under one of the compartment failure because of fire or flood during DP operation. There can be different propulsion plant layout that can be designed depending upon the size of engines and power requirement. A standard OSV propulsion plant is with four or six engines situated in two separate engine rooms, capable of producing maximum power requirement. For the DP class requirement during the DP operation all these engines are running at part loads making it inefficient. The number of engines to be installed can be lowered if the engine compartments are increased with each engine room capable of giving the full power output. This brings a challenge of space as for an OSV, maximum space availability is one of the main design criteria. On a long term basis this is a costly option by lowering the amount of space available on board. Another option is to install only one high powered engine in each of the engine rooms. This brings another challenge as during the maintenance of one of the engine it cannot conduct DP operation as any fault or failure, might cause loss of position because of the redundant system being under maintenance. Use of separate smaller sized engines only for DP operation is also not a good choice as this requires more space and increasing the number of engines to be installed, incurring more cost to the owner and the operator in terms of installation and maintenance cost.

When these big engines are replaced by lower powered engines the number of engines to be installed has to be increased to reach the maximum power requirement. Just using smaller sized engines compared to bigger sized engines is not a feasible choice as under DP operation all these engines will be under their respective part loads thus not making them more efficient compared to standard propulsion plant. To face this challenge one of the options is to install an energy storage with smaller sized engines. During the DP operation energy storage takes the high and low peak loads and makes the engine run at constant load. It is also possible that during the DP operation one of the smaller or bigger engines can be switched off and dynamic load is taken care by the engine and the energy storage. During any single fault or compartment failure this energy storage should be able to give required power output with ongoing running engine till the other engine in the compartment comes to full power.

For a AC electric transmission system there are switchboards with generators connected to them which are capable of generating full power in short time. Switchboards are required to be placed in different areas with minimum two separate engine rooms. For a DC transmission there is no requirement of switchboards as there are individual DC circuit breakers attached to the individual components even though this requires minimum two engine rooms for this vessel type. Following configurations gives overview of different power train concepts available for azimuth thrusters driven DP3 vessels.

#### Concept 1

This is standard propulsion plant layout of an offshore supply vessel with four equal sized big engines installed in two separate engine compartments. During the DP operation all this engines are running to ensure that required maximum power output is reached in short time of few seconds during the single failure or loss or compartment.

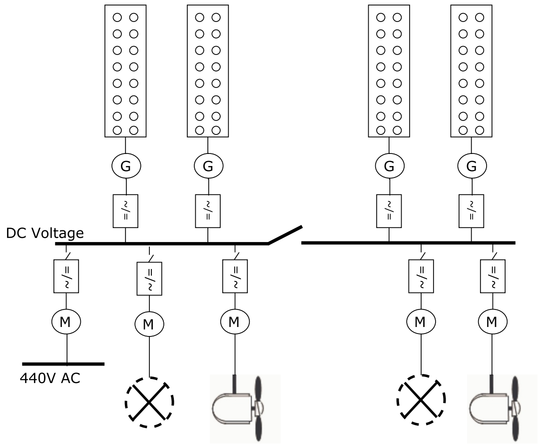



Figure 3.11: Standard propulsion system with four big sized engines

### Concept 2

This is an hybrid propulsion plant with three equal sized big engines and one smaller or medium sized engine with an energy storage. The size of energy storage is dependent on the size of engines used and the operation profile of the vessel. Here one engine room is installed with two equal sized big engines and other with one big engine, one smaller engine and an energy storage making each engine room capable of producing the maximum required power output. During the DP operation all these four engines are running with energy storage used for load levelling per engine room. There is also possibility to switch off one of the engine during this operation, with smaller engine and energy storage running in one the engine rooms. Switching off one of the engine and making smaller engine run at high load making this concept more efficient. Here the energy storage is used for load levelling, along with this it should also be capable of producing the required maximum power output for the time the bigger engine in the engine room is switched on and comes to full power for the operation. Hence energy storage also acts as the bridging power source under any single failure or loss of compartment.

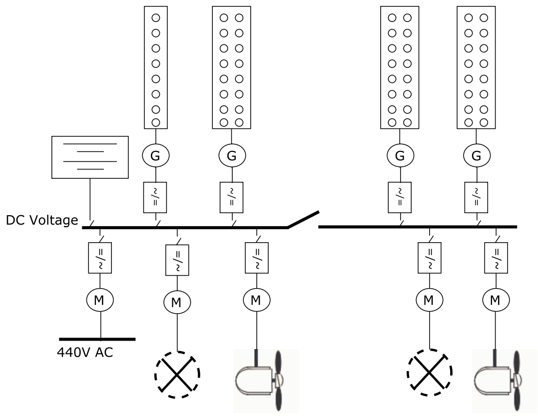



Figure 3.12: Hybrid propulsion with three big sized engine, one smaller sized engine and battery pack

### Concept 3

This hybrid propulsion plant has two big engines and two small or medium powered engine depending upon the size of energy storage used. For the class requirements each of the two engine rooms has two engines and a battery pack capable of producing maximum power under any failure condition. During the DP operation there is possibility to switch off one of the engines depending upon the size of energy storage in each of the engines rooms. Energy storage should be of an appropriate power capacity to act as bridging power source for time the other engine starts for full power operation.

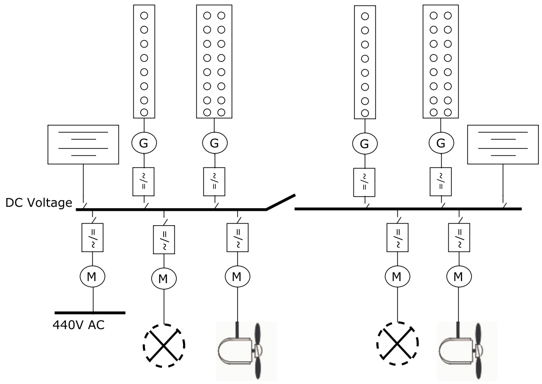



Figure 3.13: Hybrid propulsion with two big sized engine, two smaller sized engine and battery pack

### Concept 4

This propulsion plant includes three small or medium powered engines with energy storage and one bigger engine. The size of energy storage in each engine compartment is dependent on the size of engines installed in each engine compartment, with each one of them capable of producing full power under loss of one of those compartment. Here one engine room is installed with two equal sized small engines and an energy storage. The other engine compartment is with one big, one smaller powered engine with an energy storage. During the DP operation all this four engine are running with energy storage used for load levelling. There is also option to switch off one of the engines in each engine rooms during this operation with engine and energy storage taking transient load. Switching off one of the engines and making smaller engine run at high load makes this concept more efficient. Here the energy storage should be capable of producing the required maximum power output for the time other engine in the compartment comes to full power in case of failure mode. Thus energy storage also acts as the bridging power source under any single failure or loss of compartment.

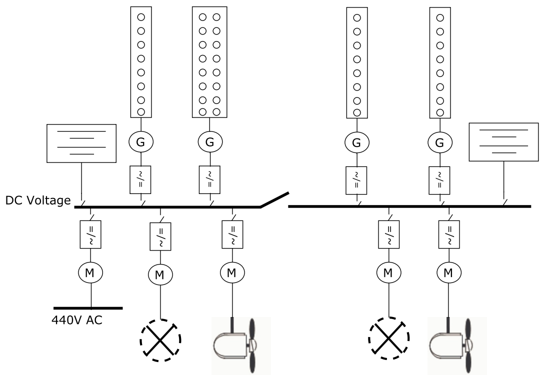



Figure 3.14: Hybrid propulsion with one big sized engine, three smaller sized engine and battery pack

### Concept 5

This is a hybrid propulsion plant with all four equal sized smaller or medium powered engines with energy storage. The size of energy storage is dependent on the size of engines used and the operation profile of the vessel. Each of the engine compartments includes two engines and one energy storage. During the DP operation all this four engine are running with energy storage taking the peak loads.Other option is switching off one of the engines in each of these engine compartments during DP operation with one engine and energy storage running. Along with load levelling the energy storage also has to act as bridging power source under any failure scenario. Compared to previous concepts smaller sized engines can be used for the same power requirement. Overall cost of this concept is higher is higher as it requires higher capacity energy storage to be installed. Hence proper size selection of energy storage in this configuration is very much important.

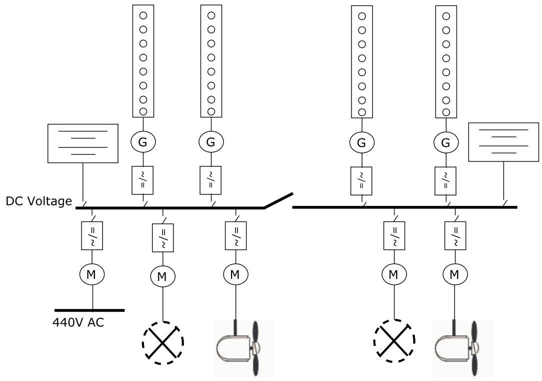



Figure 3.15: Hybrid propulsion with four smaller sized engine and battery pack

## 3.7. Performance indices

The above concepts will be compared based following common parameters:

### 3.7.1. Specific fuel consumption

It is one of the most important parameter in the design system as it includes actual work output and fuel ratio. It is defined as the mass of fuel consumed (gram) per unit produced energy($kW \cdot h$).

$$SFC = \frac{m_f \cdot 3600}{P_{eng}} \; [\frac{gm}{kWh}] \tag{3.1}$$

Where, $m_f$ = Mass of fuel consumed , $P_{eng}$ = Power produced by engine for that given mass of fuel

When the engine is running under gas mode, the gas fuel consumption is expressed as:

$$SFC[\frac{MJ}{kWh}] = SFC[\frac{gm}{kWh}] \cdot Heat\ Value\ of\ natural\ gas\ fuel\ [\frac{MJ}{kg}] \tag{3.2}$$

$$Total\ fuel\ consumed\ [MJ] = SFC[\frac{MJ}{kWh}] \cdot Power[W]\ \cdot No.\ of\ trips[-] \tag{3.3}$$

Main goal is to reduce the total fuel consumption. Total fuel consumption is expressed as:

### 3.7.2. Environmental effects

This parameter will be measured in terms of different environment affecting emissions. $CO_2$ being the significant emission for maritime industry. The emissions significant for marine industry are carbon dioxide ($CO_2$), carbon oxide ($CO$), sulphur oxide ($SO$), nitrogen oxide ($NO_x$), hydrocarbons($HC$) and particulate matters($PM$)

#### Carbon Monoxide($CO$)

Carbon monoxide is mainly formed by incomplete combustion of fuel. There are two reasons leading to incomplete combustion: [12]

- Insufficient oxygen supply
- Late fuel injection or low combustion temperature

$$C + O_2 \rightarrow CO$$

#### Carbon Dioxide ($CO_2$)

It is referred to as greenhouse gas with carbon being the main element of fuel it is formed by complete combustion of fuel. Amount of ($CO_2$) produced depends on the amount of fuel burned.

$$C + O_2 \rightarrow CO_2$$

$$m_{CO_2} = \frac{11}{3} \cdot (P_{eng} \cdot bsfc \cdot \lambda_c - m_{CO} \cdot \frac{3}{7}) \tag{3.4}$$

Sulphur Oxide ($SO_x$)
Sulphur is responsible for acid rains. Similar to carbon dioxide it is dependent on the amount of sulphur content of the fuel, hence amount of sulphur oxide produced is dependent on amount of fuel consumed.[13]

$$m_{SO_x} = \frac{64.8}{32} \cdot P_{eng} \cdot bsfc \cdot \lambda_s \tag{3.5}$$

Nitrogen Oxides ($NO_x$)
It is produced by reaction of nitrogen and oxygen present in the air at high combustion temperature. In addition to this part of nitrogen oxide is formed from the nitrogen content of the fuel burned. It contains both nitrogen monoxide($NO$) and nitrogen dioxide($NO_2$). Based on Zeldovich model formation of ($NO_x$) is given by following reactions:[12]

$$O + N_2 \leftrightarrow NO + N$$
$$N + OH \leftrightarrow NO + H$$
$$N + O_2 \leftrightarrow NO + O$$

Hydrocarbon ($HC$)
Hydrocarbons are considered carcinogenic in nature. They are formed by incomplete combustion of the fuel which contains hydrocarbon compounds. [14]

Particulate Matter ($PM$)
Particulate matter present in atmosphere is harmful to health especially the lung creating breathing problems. It s generally referred to as soot formed during combustion of fuel. It is also formed by condensation of sulphates or organic compounds. [12]

### 3.7.3. Operation cost

During the design phase of hybrid propulsion system it is important to select a proper sized engine. A detailed information about the operation profile, power requirement are necessary during the design phase in order to get the best solution. Payback time is performed as a final step to determine if the hybrid propulsion is beneficial compared to standard propulsion system. The engine size required in hybrid propulsion system are of reduced size because introduction of energy storage, in this report as battery. For the current work the cost will be limited to following: Engine cost, installation cost, fuel cost, battery pack cost and emission cost. It is necessary to include the emission cost as there is significant reduction in emission while using hybrid propulsion which can be beneficial while operating in ECA areas. Some basic assumptions to calculate total cycle cost to be calculated in American dollars ($):

- MDO fuel Price: 800 $/MT [15]
- Natural Gas fuel Price: 4.57 $/MMBTU [15]
- Engine Installation Cost: 350 $/kWh
- Battery pack cost: 550 $/kWh
- Hybrid system installation cost: 10% additional of engine installation

# 4
# Components

An overview of hybrid propulsion of DF engine with energy storage is shown in figure 4.1. This section gives information about different machineries present in the hybrid propulsion system.

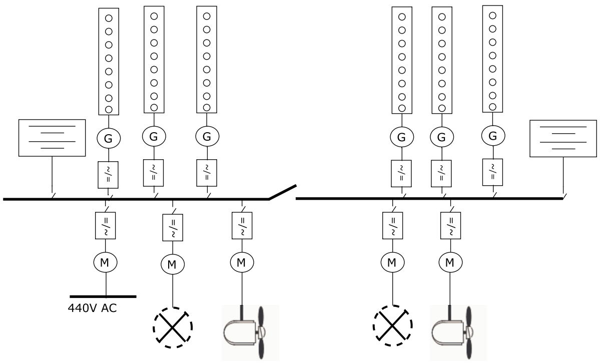



Figure 4.1: General hybrid propulsion layout

## 4.1. Gas engine

The term gas engine is used for any engine which uses gas as its primary fuel irrespective of the time for which it is being used. The use of natural gas used as fuel is dominant in its application. Following are different types of engines available in the market.

- Homogeneous Charge SI Engines
- Port Injection SI Engines
- Homogeneous Charge Pilot-Ignited Engines
- Dual-Fuel Direct Injection Engines
- Dual Fuel port injection engines

Dual fuel engine of port injection type have three types of operation principles.

- Otto operation – gas is the primary fuel and diesel fuel is used only as an ignition source
- Fuel-sharing – both the diesel and the gas contribute to the energy released; gas is still ignited by the diesel fuel
- Diesel operation – Under this mode of operation only diesel is used as fuel, with no gaseous fuel percentage Research is going on micro pilot fuel injection which will lead towards reduction of the diesel fuel consumption.

In terms of emission especially $CO_2$ natural gas has a significant reduction in its emission(gm/km). For greenhouse gas concern compressed natural gas (CNG) powered vehicles appeared to be best option. Figure 4.2 shows equivalent grams of $CO_2$ produced per km in comparison with bio gas B30 and diesel fuel for the application of vehicles.

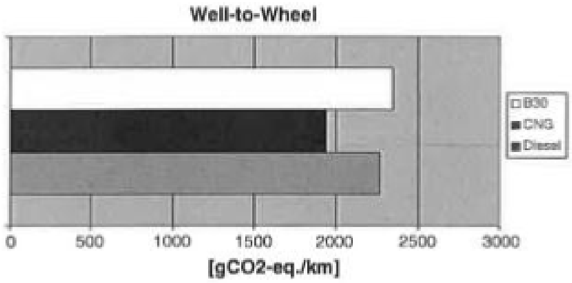



Figure 4.2: Greenhouse gas emission in gm $CO_2$-eq/km for B30, CNG and diesel fuel

But for marine industry application, use of Compressed natural gas as fuel is less suitable because of its large storage volume. This leads to the use of LNG as the primary natural gas in marine industry. The use of LNG as a fuel started with the use of boil off gas produced in the LNG tankers. This boil of gas is further used for the propulsion.

In dual fuel gas engines, under gas mode the nitrogen oxide($NO_x$) emissions are at least 85 percent below those specified under IMO regulations. Also the $CO_2$ emissions are approximately 25 percent less than the conventional marine diesel engines with only diesel as the running fuel. Also the particulate emission value decreases and sulphur oxide ($SO_x$) emission is approximately negligible. [16]

### 4.1.1. Natural gas properties

This section gives basic insight about some basic properties and composition of natural gas used as fuel in maritime industry.

The main composition of natural gas is methane along with some higher hydro carbons present into the mixture. The composition also depends on the source of the natural gas. There may be significant difference in the percentage of methane in natural gas as depending on the source. [17]

Another important characteristics of natural gas is its low burning rate and longer ignition delay compared to gasoline and diesel. [18] For a gaseous fuel two main important characteristics are its knock resistance and the calorific value. The knock resistance for a gaseous fuel is generally defined in terms of methane number. Methane number is the percentage of methane present in the natural gas. If MN<100 and as a mixture of $CO_2$ and methane when MN>100. Calorific value gives the amount of maximum energy that can be achieved per cylinder inside the engine.

### 4.1.2. Liquefied natural gas (LNG)

For natural gas the main disadvantage is its storage and the density at normal temperature. For increasing the density and volumetric density it has to be liquefied at approximately 111 K and has to be stored in high pressure storage tanks. As discussed earlier LNG is the preferred fuel for gas fuelled ships. According to major classification societies like DNV there are mainly three separate types of LNG tanks used for storage of LNG gas in liquefied state. Type A tank can be designed that is adjustable to the ship structures with pressure inside the tank lesser than 0.7 bar; type B tanks are also adjustable to the ship's structure but are generally seen in spherical shapes with pressure in the tank slightly lesser than 0.7 bar; type C tanks are cylindrical pressure tanks with pressure greater than 2 bar. Type C tanks are simple in design with easy installation so are generally used on board vessels which are not LNG carriers [19]. There are two distinguished ways of using LNG as a fuel: Natural boil off gas and forced boil off gas [20]. Natural boil off gas is taken from the top of LNG tanks with MN>100 and LCV approximately 33-35 $MJ/nm^3$. This system is generally used in LNG carriers. In forced boil off gas LNG is extracted from the bottom of the tank and evaporated in the later stage. For forced boil off gas MN<100 and LCV approximately 38-39 $MJ/nm^3$. This is the general method in using LNG as fuel in normal gas engine operated ships. Safety is also a major concern while using LNG as a gaseous fuel. There are strict rules from the classification society for the storage and use of gaseous fuels on board a ship as discussed in section 2.2 .

### 4.1.3. Factors affecting gas engine performance

There are several defined characteristic factors affecting the performance of gas engine as defined below. Each one of these factors will be explored in this section individually.

#### Compression ratio

Compression ratio plays a significant role on the performance of gas engines. In the Otto operation, engine is limited by the knock. With natural gas having higher knock resistance, a higher compression ratio engines are possible to be developed. But when in during the only diesel fuel operation a lower compression ratio is preferred to avoid knock. Thus compression ratio difference between Otto operation and diesel only operation plays a significant role in the design of dual fuel engines.

#### Engine load

In pilot ignited dual fuel engines tend to have problem while operating at low load condition. Under low load condition there is increase in duration of combustion and fuel consumption. Engine loading also have significant effect on the pollutants as follows [21]:

- $CO$- At low load there is higher emission which decreases significantly with increased load
- $NO_x$ –Because of decreased temperature inside the cylinder at part load
- $NO_x$ emission is lesser at part load
- Hydro Carbons – At low engine loads this are considerably higher
- Soot – No significant effect

Based on the loading condition it is selected under which mode the engine should be operated how much fuel sharing can be allowed. It is necessary that engine is capable of switching from gas to diesel operation or the other way around in short time without any loss of power. Figure 4.3 shows how shifting form one fuel to other occurs for a MAN 51/60 DF engine[18].

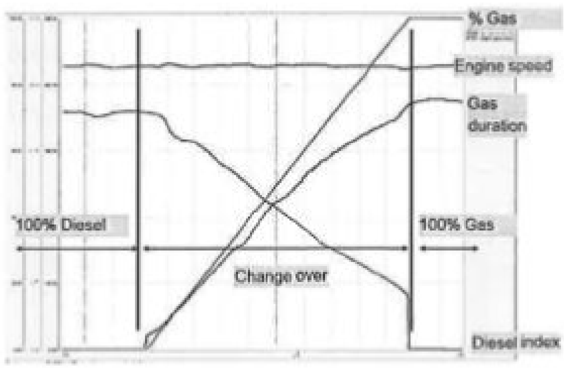



Figure 4.3: Change over from diesel to gas mode for MAN 51/60 DF engine [22]

While shifting from heavy fuel oil (HFO) to gas fuel mode precaution have to taken to prevent excess knock because of the deposits formed inside the cylinder during HFO operation. Engine load also has to set while shifting from one fuel to another. Following figure shows the operation modes for Wärtsilä Df engine for different loading conditions:

#### Pilot injection timing

In pilot ignited engines injection timing of the pilot fuel has a big influence on combustion. With advanced injection timing more fuel will be burned before the Top Dead Centre (TDC) leading to higher peak pressure near TDC and higher cylindrical peak pressures. The heat release rate is also affected by the ignition delay. Best possible fuel conversion efficiency is approximately at $45^o$ [14] . Generally injection timing are around $15^o$ before top dead centre(BTdirect Current (DC)). Injection timing also affects $NO_x$ emission. At low injection timing the temperature around the pilot fuel is higher leading to formation of $NO_x$. At higher injection timing of $55^o - 60^o$ pilot fuel has enough time to disperse leading to leaner mixture and low temperature with less $NO_x$ formation.

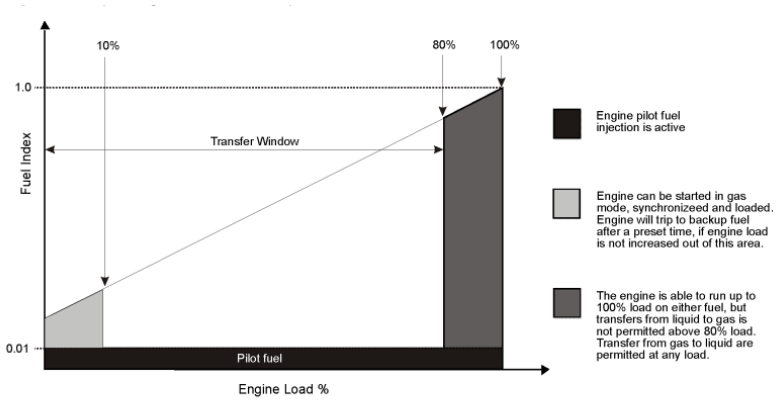



Figure 4.4: Operation mode of Wartsila DF engine [23]

### Intake manifold conditions

The ambient factors affecting gas engine operation are temperature and humidity. With increased humidity combustion duration increases leading to reduced $NO_x$ formation but at the cost of reduced efficiency. The temperature has effect on intake manifold condition. With increased temperature gas engine performance increases but leading to higher $NO_x$ emission. The ambient temperature has influence on the combustion process inside the cylinder. The inlet air temperature has effect on hydrocarbon(HC) emission with increased temperature leading to lower HC emission and vice versa. The inlet temperature is more influencing factor when the mixture used is lean. [18]

## 4.1.4. Transient behaviour of gas engine

For a dual fuel engine, the transient behaviour is an important factor. During different modes of operation the load acceptance can be different depending upon the base load at which the engine is working. In port injection types of engine with increased load more gas fuel in injected leading to rich mixture. With this the air ratio decreases leading to misfire and knock rating in Otto cycle. This factors influence more at high working load that is when engine is working at higher base load. Figure 4.5 shows the load acceptance for gas mode when compared with diesel mode for an DF engine with different base load [24].

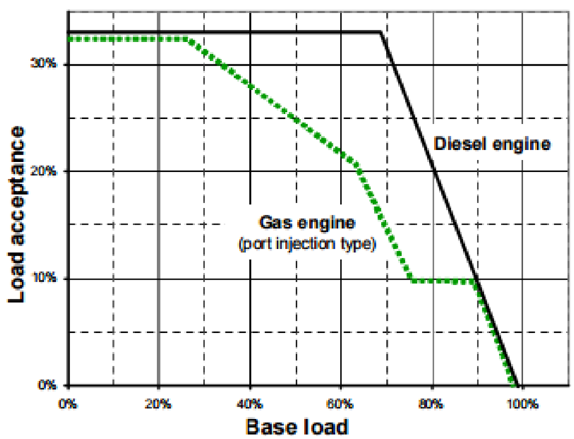



Figure 4.5: Load acceptance under gas mode and diesel mode for an DF engine

The approach used by Wärtsilä in their DF engines to represent the transient behaviour can be split it into three different factors:

- Maximum load rate
- Maximum unload rate

- Maximum instant step

During the design phase of engines a trade off needs to be done between the efficiency and emissions on one side and load response on the other side. As the lean mixture and high **bmep!** (**bmep!**) help in keeping $NO_x$ emissions low and efficiency high, they need larger turbocharger with high knock limitations. For this reason low **bmep!** engines are used in fast load response operation. For better transient charactersitics port or direct injected gas engines are used. They are also advatageous in terms of achieving the requirements for double walled gas piping system for to be installed in conventional engine rooms. Diesel ignited gas engines are better suited for steady medium- high load applications where there are more engines connected to certain load and limit the transient loading condition. Diesel gas engines have good part load and transient loading condition which is similar to conventional diesel engine given that the gas fuel system has good capability to handle variable loads.

### 4.1.5. Emissions

The following section explains emissions during three different operation cycles of gas engine. The emission is higher depending upon the cylinder process or the mode of engine.

#### Emissions under otto operation

Under Otto operation or the extremely lean mixture engine has the potential to achieve extremely low $NO_x$ emissions because of the relatively low temperature inside the cylinder. The compromise during lean mixture has to be made between hydro carbon emissions and emission. Air excess ratio has great influence on emissions for this mode of operation.

#### Emissions under diesel only operation

Emissions from diesel operation in an dual fuel engine is similar to normal diesel engine with only variation in the emission of $CO_2$ emission because of the lower carbon content fuel being used in DF engines.

#### Emission under dual fuel operation

The development of dual fuel engines was because of the lower $NO_x$ emission. But this low emission was achieved through compromise in other emissions. Carbon monoxide (CO) emissions are significantly higher for dual fuel operations because of the pre ignition taking place in the methane air mixture during the compression stroke of engine [13]. In DF engines soot is formed only from the fuel oil which gradually decreases with increasing gaseous fuel percentage.

### 4.1.6. Efficiency

Depending on the working condition the efficiency of gas engine can be higher or lower than the diesel engines. Compared to diesel engines of same maximum pressure gas engines have lower **bmep!**. In general gas engines are bit more efficient than the diesel engines in terms of power (kW) but not in break mean effective pressure (BMEP).Depending on the working condition the efficiency of gas engine can be higher or lower than the diesel engines. There are many factors affecting efficiency of gas engine of which few main are as follows[17]:

- **Specific load:** At higher load the efficiency increases because of the relatively low effect of the losses (frictional, auxiliary and heat) and hence fuel consumption decreases at higher loads.
- **Cylinder bore:** With increased cylinder bore the heat loss decreases because of the decreased area to volume ratio leading to higher efficiency.
- **Compression ratio:** With increased allowable methane number, would result in increased compression ratio leading to higher efficiency.

Maximum attainable efficiency from a gas engine is approximately 49% .[17]

## 4.2. Energy storage

Energy storage has many unique plus points. An example of this may be, there are no direct emissions associated with operation of most of the energy storage. These devices can supply on peak power demand effectively without adding emissions to the system.

Energy storage devices like power generators have some basic operational parameters. Energy storage can act both as electrical energy generation and a load on the system during the storage. Generation of energy from energy storage is energy limited with maximum output limited by the amount of energy previously stored. Energy storage's ability to act as load brings with it some important benefits which will be discussed later.

Based on the purpose for which the energy storage is used it can be classified in following types:

- Peak Shaving
- Frequency keeping
- Load levelling
- Main power source
- Spinning reserve

### 4.2.1. Brief about different energy storage

This section will give brief description about different energy storage technologies with idea about the cost and their technology. The broadest definition of energy storage is any system which absorbs energy in some form at one time and releasing the same energy at later instance of time. Most of the energy storage devices work on the principle of storing electrical energy in which electrical energy is absorbed at one time and released later at controlled rate. Most of the technologies convert the electrical to be stored in other form of storage. Figure 4.6 gives classification based on the form of energy that is stored [25].

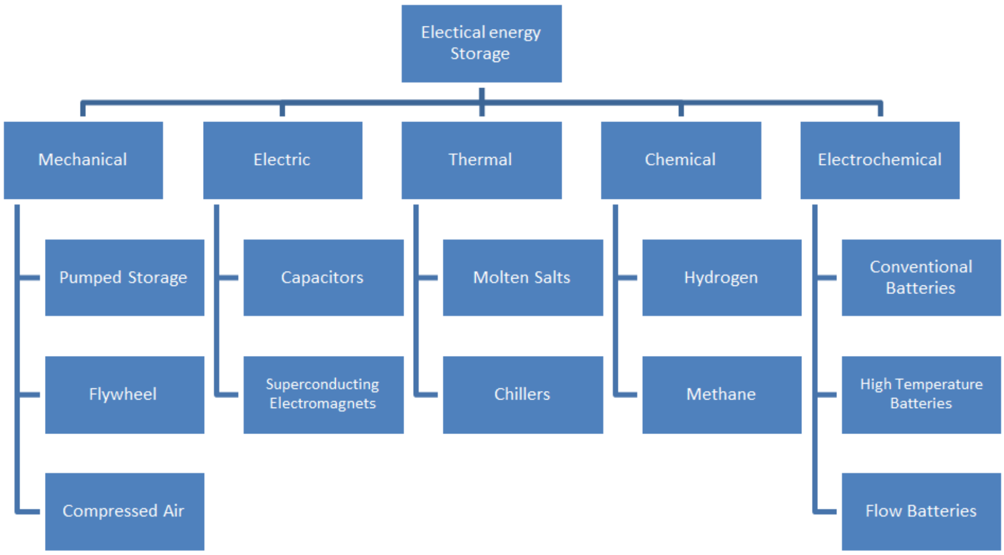



Figure 4.6: Classification different energy storage technologies

Table 4.1: Operation requirements for different types of energy storage

| Requirements | Long Discharge Frequent Use | Short Discharge Frequent Use | Long Discharge Infrequent Use | Song Discharge Infrequent Use |
|---|---|---|---|---|
| Discharge Duration | Hours | Minutes | Hours | Seconds |
| Response Time | Minutes | Seconds | Minutes | Seconds |
| Discharge Depth | Deep | Shallow | Deep | Shallow |
| Minimum Cycle Life | Few 1000s | Ten 1000s | Ten 1000s | Few 1000s |
| Energy Efficiency | Important | Important | Not important | Not Important |

Brief comparison of energy storage devices on some important attributes [25]:

Table 4.2: Energy storage overview

| Technology | Cost ($/kW) | Cost ($/kWh) | Efficiency | Cycle Limited | Response Time |
|---|---|---|---|---|---|
| Pumped Hydro | 1,500 - 2,700 | 138 - 338 | 80-82% | No | seconds to minutes |
| Compressed Air (Underground) | 960 - 1,250 | 60 - 150 | 60-70% | No | seconds to minutes |
| Compressed Air (Aboveground) | 1,950 - 2,150 | 390 - 430 | 60-70% | No | seconds to minutes |
| Flywheels | 1,950 - 2,200 | 7,800 - 8,800 | 85-87% | >100,000 | instantaneous |
| Lead Acid Batteries | 950 - 5,800 | 350 - 3,800 | 75-90% | 2,200 - >100,000 | milliseconds |
| Lithium-ion Batteries | 1,085 - 4,100 | 900 - 6,200 | 87-94% | 4,500 - >100,000 | milliseconds |
| Flow Batteries | 3,000 - 3,700 | 620 - 830 | 65-75% | >10,000 | milliseconds |
| Power To Gas | 1,370 - 2,740 | NA | 30-45% | No | 10 minutes |
| Capacitors | - | - | 90-94%13 | No | milliseconds |
| SMES | - | - | 95%14 | No | instantaneous |

Based on the comparison in table 4.2 comparison the suitable choice of energy storage that can be used for marine applications are:

- Flywheel
- Batteries (Electrochemical energy storage)
- Super capacitors (Electromagnetic energy storage)

### 4.2.2. Flywheel

Flywheels store electrical energy by speeding the inertial mass mainly the rotors. This rotating mass rest on low friction bearings in evacuated chambers to reduce the friction as much as much as possible. Energy is transferred to the shaft of rotating mass using a motor generator. Rotor is the main component of flywheel. Rotor characteristics like the inertia, rotational rate and material density determine the energy that can be stored and density of the device. The motor generator connected to the flywheel determine the maximum power of the flywheel. Currently flywheel range from 100kW to 2MW with discharge time from 5 seconds to 15 minutes. Total round trip efficiency of flywheel is around 70-80% with approximately 2-3% standby losses which may occur due to friction inside the housing.

Flywheel are generally used for short discharge duration application with instantaneous response time, making it common choice for uninterrupted choice for constant power supplies. Main concern in using flywheel as energy storage is mechanical wear because of the frequent cycle and continuous operation. Limited by the mechanical wear and power rating power rating flywheel have general life cycle of approximately 100,000 charge and discharge cycle.[26]

Generally, flywheel energy storage (FES) are divided into two categories: low speed and high speed systems. First group speed reaches several thousand rpm (in this category flywheel is mostly metallic and using mechanical bearing is common) while the second group has tens of thousands rpm (To increase efficiency, composite materials, and to reduce friction and mechanical losses, magnetic bearing are commonly used in the flywheels of this category). The energy stored by the flywheel is dependent on the square of the rotating speed and its inertia. Here inertia itself depends on the flywheel mass and geometry.

The energy is stored in a rotating mass and the amount of energy stored is a function of the moment of inertia and angular velocity, as shown in following equation [27]:

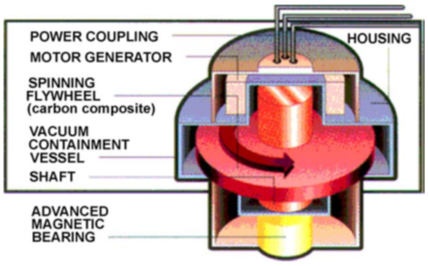



Figure 4.7: Main components of flywheel energy storage [26]

$$E = \frac{1}{2}(I * \omega^2) \quad [J] \tag{4.1}$$

where, $E$ = energy stored, $I$ = moment of inertia and $\omega$= angular velocity

Moment of Inertia,

$$I = mr^2 \quad [kg\ m^2] \tag{4.2}$$

Where $m$ = mass of flywheel, $r$ = radius of flywheel

The amount of energy that can be stored inside a flywheel is limited by the tensile strength of the material. If the stresses in the material of flywheel exceed the material tensile stress limit, flywheel will break apart. Tensile stress can be given as:

$$\sigma_{max} = \rho r^2 \omega^2 \quad [\frac{N}{m^2}] \tag{4.3}$$

Where $\sigma_{max}$ = Maximum tensile strength, $\rho$= Material density

Energy density and specific energy for a thin rim flywheel can be expressed as:

$$e_{k,m} = \frac{1}{2}\frac{\sigma_{max}}{\rho} \quad [\frac{J}{kg}] \tag{4.4}$$

$$e_{k,v} = \frac{1}{2}\sigma_{max} \quad [\frac{J}{m^3}] \tag{4.5}$$

Where, $e_{k,m}$= specific energy, $e_{k,v}$ = energy density

Thus a flywheel which is made of higher density material such as steel, would be able to store more energy compared to equivalent flywheel of lower density material with same angular velocity. However lower density material develop lower internal stresses compared to higher density material allowing them to rotate at higher angular velocity. This feature allows to store same amount of energy in smaller sized flywheel rotating at higher angular velocity.

### 4.2.3. Electrochemical energy storage

Electrochemical energy storage devices works on the principle of converting electrical energy into chemical potential energy for storage and further using it to produce electrical energy back again. Batteries can be classified into three types : conventional, high temperature, and flow [25]. Only drawback of battery storage is its limited life cycle because of the electrode fouling and electrolyte degradation.

### Conventional batteries

Conventional batteries contain positively charged anode and negatively charged cathode which are packed in a sealed package to form a cell. These electrodes are separated by electrolyte. During the charging cycle this electrolyte is ionized, during discharge because of oxidation reduction reaction the energy is recovered from the cell.

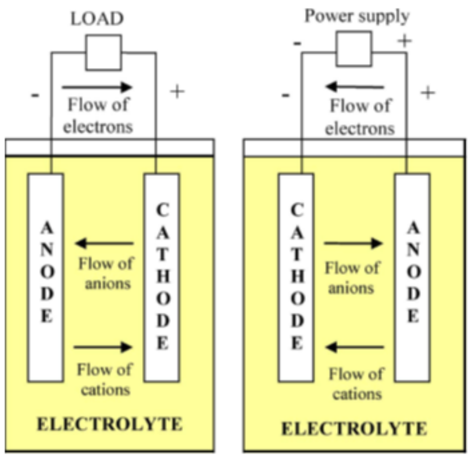



Figure 4.8: Schematic of rechargeable battery[26]

### Lead acid

Lead acid batteries are the most advanced batteries under the family of electro chemical energy storage. It is popular choice for energy storage because of its low cost. These batteries are suitable for power quality application with roundtrip efficiency of approximately 75-85%. The expected working life of lead acid batteries is 3-10 years depending upon the working environment. The main drawbacks of lead acid batteries are toxicity, low specific energy and power, high maintenance requirements and short life cycle operation.

### Nickel-cadmium

These batteries have relatively low round trip efficiency between 60-70%. Being more expensive than conventional lead acid batteries these are still better choice in energy storage application because of longer life span of around 10-15 years. Only drawback of nickel cadmium battery is cadmium being highly toxic in nature.

### Lithium-Ion

This is the most used battery around the world now a days starting from consumer electronics on small scale to high energy storage. The reason for its extensive use is its high energy density and low stand by losses compared to other devices. Lithium-ion batteries are still facing the cost barriers. The average round trip efficiency of lithium-ion batteries is approximately 85-95% with an operational life of 10-15 years depending on charging and discharging cycle. The nominal voltage of Li-ion is 2.7 V.

When the battery is discharged, lithium ions in the carbon electrode from the anode migrate to the cathode via separator. At the same time electric current flows through the external circuit. During the charging process of battery electric current is forced in the opposite direction with lithium ions migrating via a separator to the anode.

The lithium ions are stored in layered grids of carbon or graphite, while the electrons are being absorbed or released at the same time. These ions are discharged during this process but no significant chemical combining occurs.

Overall chemical reaction in a Li-ion cell is as follows [28]:

$$C_6 + LiCoO_2 \longleftrightarrow LiC_6 + Li_{0.5}CoO_2$$

At the cathode:

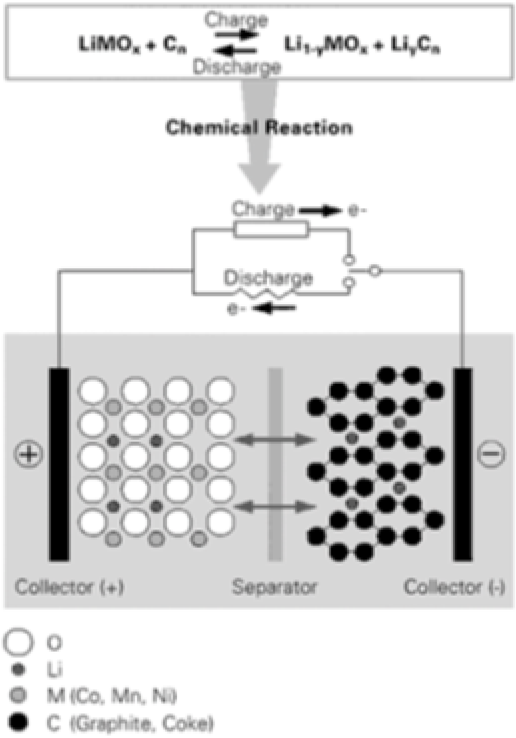



Figure 4.9: Basic principle of Li-Ion battery [28]

$$LiCoO_2 - Li^+ - e^- \longleftrightarrow Li_0.5CoO_2 \Rightarrow 143\frac{mAH}{g}$$

At the anode:

$$6C + Li^+ + e^- \longleftrightarrow LiC_6 \Longrightarrow 372\frac{mAH}{g}$$

Over discharging limits above reaction by supersaturating lithium cobalt oxide leading to production of lithium oxide by an irreversible chemical reaction.

$$LiCoO_2 + Li^+ + e^- \longrightarrow Li_2O + CoO$$

Generally cells charge up to 4.2 V with a cell tolerance of $+/-$ 50 mV. Overcharging till 5.2 V will make the battery unstable for use. Prolonged charging above 4.3V will form plating of metallic lithium on the anode, while cathode becomes oxidizing agent losing the stability and producing carbon dioxide. Pressure and temperature rises because of overcharging the cell.

### 4.2.4. Key battery parameters

This section describes some important parameters that affects the battery performance.

#### Battery life cycle

It is the number of charge-discharge cycle a battery can undergo before the nominal capacity of battery falls below 80% of its initial rated capacity.

#### Depth of discharge

At a given temperature and discharge rate, the amount of active chemicals transformed with each charge discharge cycle will be proportional to the depth of discharge (DOD). The relation between the cycle life and the depth of discharge appears to be logarithmic as shown in the figure 4.10. In other words, the number of cycles yielded by a battery goes up exponentially with shallower DOD. This holds for most cell chemistries.

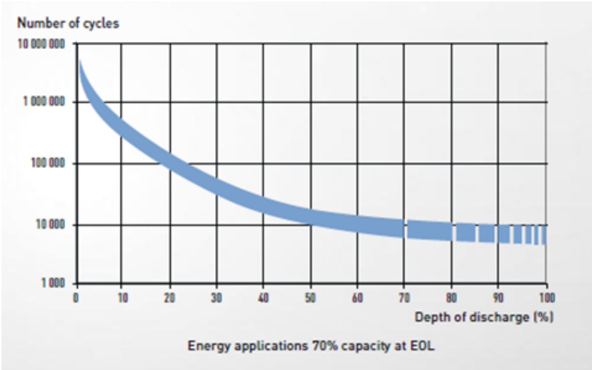



Figure 4.10: Effect of DOD on battery life cycle [25]

#### Charging rate

The charging rate of battery has strong influence on its life cycle. At high discharge rate the the chemical reaction cannot work with high rate of current being drawn resulting in reduced capacity. Similarly at high charging rate or forcing higher current through the battery during the charging may result in more ions deposited on the anode resulting in loss of capacity. There is limitation on the fast charge and discharge for lithium ion batteries.

#### Charging level

The cycle of Li-ion batteries can be increased with reduced charging cut–off voltage. Charging cut-off voltage is the voltage at which the battery is considered fully charged and to stop further charging of the battery. This gives battery a partial charge instead of full charge which is similar to working at lower depth of discharge.

#### Temperature

Higher working temperature of battery will increase the performance of battery in terms of power, with compromise on unwanted chemical reactions resulting in loss of battery life. Arrhenius equation shows relationship between chemical reaction rate and temperature as follows:

$$k = Ae^{-\frac{E_A}{RT}} \tag{4.6}$$

Where,
$K$ = rate of chemical reaction, $A$ = frequency factor, $e$ = 2.71828, $E_A$=activation energy, $R$= universal gas constant, $T$=temperature in Kelvin

### 4.2.5. Electromagnetic energy storage

Unlike other energy storage technologies capacitors and superconducting electromagnets are capable of storing the electrical energy in its original form, making this kind of energy storage highly efficient.

#### Supercapacitors

Supercapacitors also known as ultra-capacitors are made of two electrical conductors separated in fractions of nanometre by a non-conducting material called dielectric. The supercapacitors are similar to regular capacitors with only difference that it has very high capacitance in small package. During the charging process the plates build up electrical charge on either side. Energy is stored in form of electric field in between charged electrode plates. Super capacitors have higher energy density and capacitance in the range of farads which is much higher compared to electrostatic capacitors. The general working voltage of these devices is 2.5-2.7

V which gradually decreases with energy dissipation. Voltages of 2.8 V or higher is possible by connecting the super capacitors in series. Supercapacitors have lower specific energy density compared to batteries and higher specific power density. Because of these characteristics this technology is used in providing power gaps for short duration of time which may in the range of few seconds. The charging time of supercapacitors is also small in the range of few seconds. Since energy is not stored in form of electrochemical reaction the life cycle of super capacitors is infinite or practically no degradation in energy storage efficiency. Supercapacitors can be connected in series for higher voltage or in parallel for higher energy requirements.

The amount of charge that can be stored in relation with the applied potential is known as the capacitance, which itself is the measure of energy storage capability. [29]

$$C = \frac{Q}{V} = \epsilon \frac{A}{d} \tag{4.7}$$

$$U = \frac{1}{2} C V^2 = \frac{1}{2} Q V \tag{4.8}$$

Where,
$C$ =capacitance in Farads, $Q$ =charge in Coulombs, $\epsilon$ =dielectric constant, $A$ =conductor surface area, $d$ =dielectric thickness, $U$ =potential energy

On charging the, voltage increases gradually, with current dropping by default when the capacitor is fully charged without the need of charge detection circuit. On discharging the super capacitor, the voltage decreases gradually and to maintain constant steady power the converter draws more current. The capacitor is discharged when load requirement can no longer be met. Generally charging time of super capacitors is in the range of 10 -15 seconds. Overcharging of super capacitor is not possible hence it does not require full-charge detection.

The supercapacitors have virtually infinite number of cycles and hence can be charged and discharged unlimited number of times. Ageing is also not a major factor when using supercapacitors for energy storage. Supercapacitors fades from 100% capacity of energy storage to 80% in 10 years or more, however applying a higher voltage may result in reduced life. Super capacitors are also temperature independent with capability to work normally at moderate cold to hotter working temperatures.

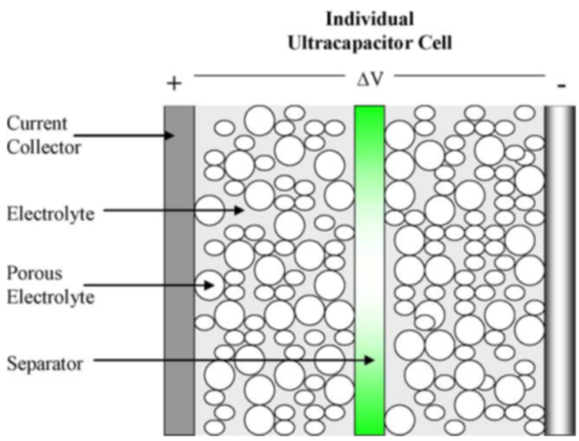



Figure 4.11: ECDL super capacitor cell [26]

These capacitors are still in research stage to realize their full potential. Some main drawbacks of super capacitors:

- Sensitivity to the voltage- higher applied voltage may result in reduced life

- Lower specific energy density- This devices gets discharge in few seconds so cannot provide energy for longer duration

## 4.3. Electric machines

This section gives insight about main electric machines used in hybrid propulsion system.

### 4.3.1. Generator

The generator for a DC distribution system can be of three types: DC, Synchronous and Induction generator.

The limitation of DC generator is its high commutation losses during high power application, thus limiting its use in marine application. For an induction generator the maximum speed is limited by the synchronous frequency of the network. This limits the speed range of the induction generator. To handle both the above issues and run the generator with wide speed range synchronous generator is used for DC distribution system. The power of synchronous generator can be given as:

$$P = kD^2 IBAf_m \tag{4.9}$$

Where,
D = Air gap diameter, L = active length, B = magnetic loading (air gap flux density), A = electric loading (line current density), $f_m$ = mechanical frequency (Hz), k = proportionality constant

The power density is proportional to the rotor speed of the generator. Thus to produce higher power generator has to be rotated at higher speed. This can be further improved by using high speed prime mover or by increasing number of magnetic poles.

$$F = \frac{p * n}{120} \tag{4.10}$$

Where,
f = synchronous frequency of a synchronous generator, p = number of magnetic poles, n = synchronous speed of the rotor in revolutions per minute (rpm)

Increasing the number of poles leads to different limitations like the weight, noise and cost. A proper selection of speed and number of poles has to be done during the design phase. In synchronous generator with brushes or brush less exciter large pole pitches are required to support the field winding. In permanent magnet synchronous generator number of poles can be high with smaller size and weight. Further permanent magnet synchronous generator replaces exciter with definite brush less structure thereby improving the efficiency and reducing the overall size. The synchronous frequency of the generator is chosen as high as possible in the working profile of the prime mover. Higher frequency results into higher copper and stator losses which has to be taken into consideration during the design of permanent magnet synchronous generator.

### 4.3.2. Motor

The motor used in propulsion are of fours types: DC, asynchronous, synchronous and permanent magnet synchronous motors.

Permanent magnet synchronous motor (PMSM) is alternating current driven motor. As there is no commuter or slip ring in its construction it requires less maintenance. Excitation losses are also null as electrical energy is not absorbed by means of field excitation. Also alternating current (AC) motors are smaller and lighter than DC motor hence they are best choice for electric propulsion. The size of electric motor is decided upon type of operation mode and installed engine power. Electric motor works on the principle of Lorentz force on the rotor. Torque produced by electric motor is given by:

$$M = K_M \cdot \phi \cdot I \tag{4.11}$$

Where,
$K_M$ = Motor constant which depends on number of winding and flux density variation; $\phi$ = flux density which depends on type of material; I = winding current

## 4.4. Electrical network

Electric machines are operating on two different electric networks that are Alternating current (AC) network and Direct current (DC) network. A proper selection of electrical network has to be done depending on the choice of machine selection and their advantages.

#### AC network

The purpose of using AC distribution propulsion system is to replace current main diesel engine operation with a system of diesel engine running the generator and there by the electric motors with much higher efficiency, and split the power production to increase the redundancy of each unit in the system. A configuration can be designed based in the type of vessel to operate at highest efficiency by selecting the number of generators running at given load profile. A general configuration of diesel electric propulsion system includes diesel engines driving the generators and produce electric power. Prime movers mentioned in the can be diesel engines or gas turbines for high power requirements. The electric power is further distributed by the switchboards to each unit. For the redundancy there are more than one switchboard on-board the DP3 class ship. Voltage level in the electric circuit is controlled by the load requirement i.e higher the load required, the higher voltage level in the circuit. Main propulsion and thruster motors are the prime consumers of electric power. The motor drives are usually asynchronous when power demand are low and synchronous for higher power demands. Transformers are needed to control the voltage as different power consumers operate at different voltage levels.

For controlling the speed of the motors a frequency controller is installed in the circuit. A power management system controls and monitors the overall working of the entire system. With increase in load more generators are started thereby connecting them to the power network.

#### DC network

The main advantage of DC network is its design, control and protection system with optimized energy flow.[8] There are multiple ways to configure DC network based on application. In multidrive approach all the converter modules of the netowrk are located at the same level similar to AC switchboard. Under distributed layout the converter module are placed as near as possible to the power source or the consumer.

The relevant components of high voltage direct current system (HVDC) are:

- A thyristor or IGBT valves to realize the conversion of AC to DC voltage and thus being the main components of HVDC converters
- The smoothing reactors to prevent the discontinuous current and resonance in the DC circuit
- DC transmission lines consisting of DC transmission line cables, DC switches and earthing electrodes

Figure 4.12 shows a simple DC distribution network

### 4.4.1. Advantages of DC grid over AC transmission

#### Efficiency

A study conducted by ABB shows a DC distribution grid can improve as much as 20% of less fuel consumption. Vessels with dynamic load profile or varying operation loads have maximum gain using DC grid for the electric propulsion. In DP vessels while the dynamic positioning operation will lead to higher fuel efficiency with varying continuous load.

#### Weight and space

Beside the efficiency increase other main benefits of DC network over AC network are increased space because of elimination of switchboards and weight saving by up to 30%. This allows to carry more cargo for same fuel consumption and a more functional vessel design. [30]

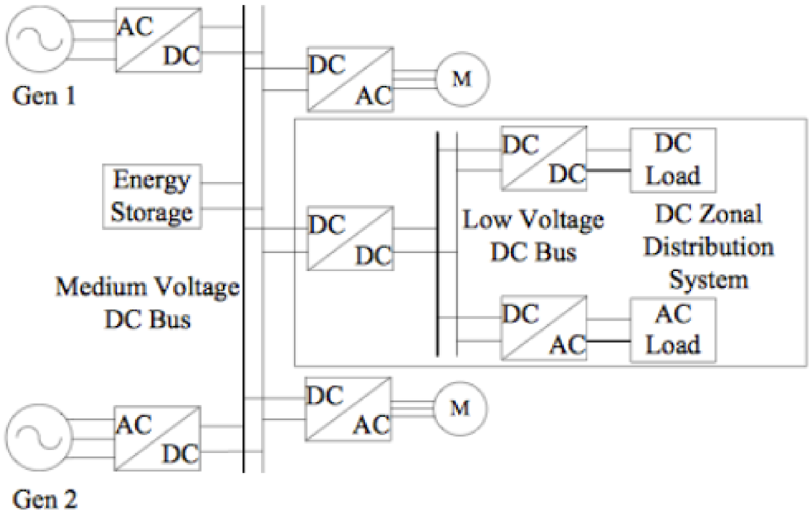



Figure 4.12: Schematic of DC grid

### Network safety

Unlike AC, DC network does have fuses or controlled switches. In short like the fuses in AC network, isolated inverter modules are used in DC network in case of serious faults occurring in the module. The input circuits separate the inverter module from the DC bus allowing full control of reverse power under normal working operation or in faults. Thus when there is fault in single consumer, it would not affect the main DC network. In case of multiple consumer failures the network is protected from generator side by means of controllable thyristor converter. For each consumer and source isolators are used for individual circuits for the normal workability of DC network under any fault condition. The response time of fault current is 40 ms thus reducing DC grid fault energy level compared to AC protection grid which has fault duration can reach upto 1s.[30]

### Operation

Engines operating on LNG as fuel are well suited for DC grid power distribution to work at stable loads with higher efficiency reducing methane slip and emission of $CO_2$,$NO_x$ and $SO_x$. Another advantage of using DC power grid is easy integration with the energy storage devices which all run on DC. Under AC network it is crucial for engines to run at constant speed to keep the generator frequency at 60 Hz unlike the DC grid where engine operation can be at wide speed range making operation profile of engine wider and efficient.

### 4.4.2. Network voltage

The DC bus voltage will be decided upon the generator voltage and the power requirement from the generators. Battery voltage is also taken into consideration while deciding the bus voltage. A bus voltage higher than battery voltage is safe and easy choice for network voltage[31]. Number of generators connected to the DC bus also affect the bus voltage as power required from the bus is transferred to the generators, hence a lower value of voltage is possible when number of generators connected to the network are more. A higher value of bus voltage is preferred as high voltage means lower current in the system. A lower value of current means lower ohmic losses with lower temperature condition.

## 4.5. Power management system

Onboard the ship there are different consumers which require different power. All the power for the whole system is governed by control systems like the off-loading control system involves the drives of cranes and pumps or a position system controls the thruster drives. The power management system acts as the controller of the whole power network which controls and monitors each subsystem. The prime function of power management system is to start / stop of generators and match with the desired load requirement.

It also monitors the energy flow for the optimal fuel efficiency. It is also sometimes referred as energy management system. The blackout of system may occur if there is any fault in power management system putting life of crew onboard and equipment in danger. To prevent complete blackout of the system different measures are taken like the start and stop functions, load shedding of non-critical load and reduction of load. A back up system is also integrated to start up and reconfigure the power system. The power management functionality depends on the plant configuration, power requirement and operation profile of the vessel.[32]

Main tasks performed by power management system are listed below:

- Starting / stopping of generators
- Starting / stopping of generators in under frequency or under voltage in cases of faults
- Distribution of load between generator sets and energy storage
- Handling and blocking of active loads
- Bus breaker monitoring and control
- Automatic load shedding

# 5
# Modelling

This chapter gives details about modelling of different components in Matlab/Simulink and approaches used to model them. It also explains system integration of generator with the engine, generator with the DC Bus and motor. The lithium ion polymer battery used as energy storage model is integrated with the power plant model through the DC bus. The components are modelled based on first principle approach with their individual physical process expressed in form of numerical equations. Gas is based on mean value first principle model.

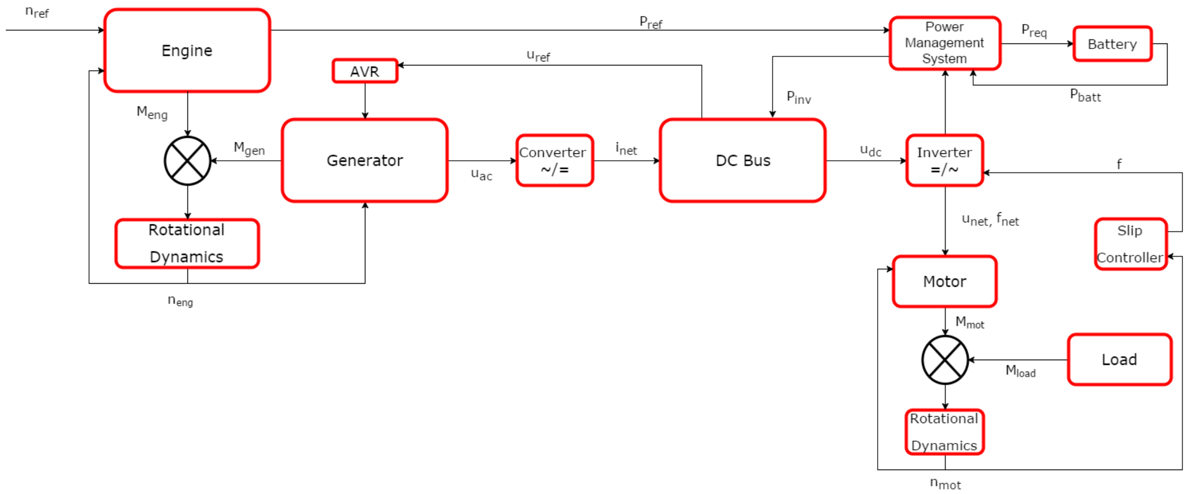



Figure 5.1: Model overview

## 5.1. Gas engine

The dual fuel engine model used for this thesis is Diesel A5 model developed by MTI Holland. This model is based on the Diesel A4 model of Delft university of Technology. The top layer of engine model consists of engine speed controller, the diesel fuel (main and pilot) fuel pump, gas fuel pump and the engine core.

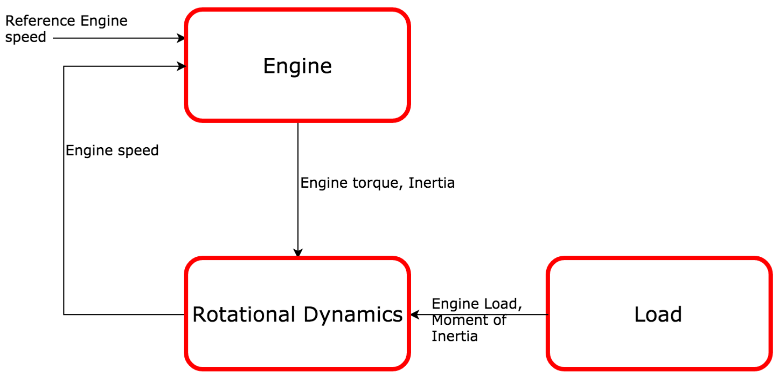



Figure 5.2: Engine model overview

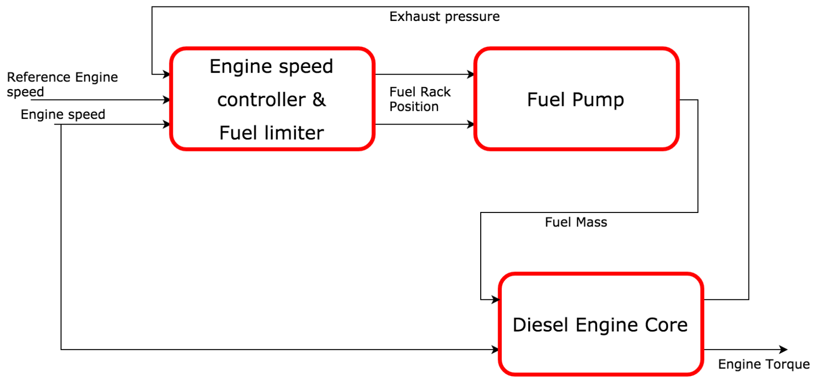



Figure 5.3: Engine internal overview

### 5.1.1. Closed cylinder

The closed cylinder process is based on the 5 point seiliger cycle. This part of engine model consists of different cylinder process with heat release model and total power calculator.

### 5.1.2. Seiliger cycle

Seiliger cycle is known as dual combustion cycle as a combination of Otto cycle and Diesel cycle. The engine model is based on this cycle as it allows prediction of fuel consumption, power of diesel engine with reasonable accuracy. The five points of seiliger cycle are:

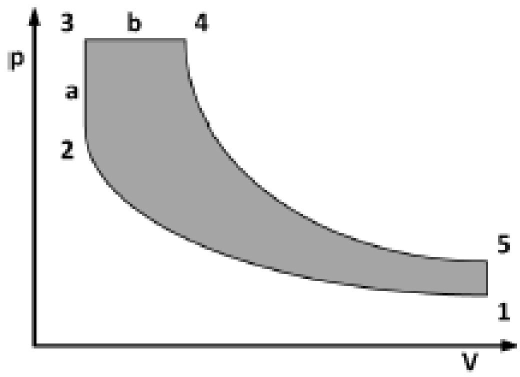



Figure 5.4: Seiliger cycle

- Adiabatic compression (1-2);
- Isochoric combustion (a) (2-3);
- Isobaric combustion (b) (3-4);
- Adiabatic expansion (4-5);
- Rejection of heat (at a constant volume) (5-1)

#### Compression process

This process involves compression of air-fuel mixture in preparation for the ignition during power or combustion stroke. This process is modelled using inlet parameters ($P_1$ and $T_1$), cylinder compression volume ($V_1$ and $V_2$) gas constant and specific heat of air at constant pressure ($c_{p,air}$) and constant volume ($c_{v,air}$). [33]

$$p_2 = p_1(\frac{V_2}{V_1})^{n_c} \quad [Pa] \tag{5.1}$$

$$T_2 = T_1(\frac{V_2}{V_1})^{n_c-1} \quad [K] \tag{5.2}$$

$$w_{1-2} = \frac{R_{air}}{n_c - 1}(T_1 - T_2) \quad [\frac{J}{kg_{air}}] \tag{5.3}$$

Isochoric combustion

The combustion process in seiliger cycle is isochoric that means the volume at the start and end of combustion stage is same($V_3 = V_2$), hence this stage does not produce any work. The combustion stage is modelled using following equations:[33]

$$a = 1 + \frac{q_{cv}}{c_{v,air} * T_2}[-] \quad (Isochoric\ Combustion\ parameter'a') \tag{5.4}$$

$$p_3 = a \cdot p_2 \quad [Pa] \quad (Pressure\ after\ combustion\ stage) \tag{5.5}$$

$$T_3 = a \cdot T_2 \quad [K] \quad (Temperature\ after\ combustion\ stage) \tag{5.6}$$

Isobaric combustion

This stage of combustion has same pressure at the start and end of the process($p_3 = p_4$). This stage of combustion is modelled using following equations: [33]

$$b = 1 + \frac{q_c p}{c_{p,air} * T_3} \quad [-](Isobaric\ combustion\ parameter\ 'b') \tag{5.7}$$

$$T_4 = b \cdot T_3 \quad [K](Temperature\ after\ isobaric\ combustion\ stage) \tag{5.8}$$

$$w_{3-4} = R_{air} * (T_4 - T_3)\frac{J}{kg_{air}} \quad (Work\ from\ isobaric\ combustion\ stage) \tag{5.9}$$

Expansion

The pressure temperature and work at the end of expansion stroke are calculated using following equations: [33]

$$p_5 = p_4(\frac{V_4}{V_5})^{n_e} \quad [Pa](Pressure\ after\ the\ expansion\ stage) \tag{5.10}$$

$$T_5 = T_4(\frac{V_4}{V_5})^{n_e-1}[K](Temperature\ after\ the\ expansion\ stage) \tag{5.11}$$

$$w_{4-5} = \frac{R_{air}}{n_e - 1}(T_4 - T_5)[\frac{J}{kg_air}](Work\ from\ the\ expansion\ stroke) \tag{5.12}$$

### 5.1.3. Heat release module

The heat release module calculates the heat released during the two stage of combustion. [34]

- The heat released during isochoric stage is $q_{cv}$
- The heat released during isobaric stage is $q_{cp}$

The equations for heat released are expressed in terms of total heat released ($q_{in}$) and the percentage of heat released during isochoric combustion ($X_a$).

$$q_{cv} = q_{in} * X_a \, [\frac{J}{kg_{air}}](Isochoric\ combustion\ heat) \tag{5.13}$$

$$q_{cp} = q_{in} * (1 - X_a)[\frac{J}{kg_{air}}](Isobaric\ combustion\ heat) \tag{5.14}$$

### 5.1.4. Mass flows

The total fuel mass is calculated per cylinder on per cycle basis. The total air and fuel mass flow is expressed in terms of engine speed as follows:[34]

$$\phi_{f,tot} = m_{f,tot} * \frac{n_{eng}}{k_{eng} \cdot i_{cyl}} \, [\frac{kg}{s}] \, (Total\ fuel\ mass\ flow) \tag{5.15}$$

$$\phi_{air,cyl} = m_1 * \frac{n_{eng}}{k_{eng} \cdot i_{cyl}} \, [\frac{kg}{s}] \, (Total\ air\ mass\ flow\ from\ the\ cylinder) \tag{5.16}$$

### 5.1.5. Power calculation

This module calculates the total power, torque and mechanical losses of the engine. The total work of the engine is sum of all the work of individual cycles. [35]

$$w_{cyc} = w_{1-2} + w_{2-3} + w_{3-4} + w_{4-5}[\frac{J}{kg_{air}}](Cyclework) \tag{5.17}$$

$$M_{eng,no\ loss} = \frac{m_1 \cdot w_{cyl} * i_{cyl}}{k_{eng} * 2 * \pi}\ [Nm](Torque\ without\ mechanical\ losses) \tag{5.18}$$

$$M_{eng} = M_{loss,c} + M_{loss,n} \cdot \frac{n_{eng}}{n_{eng,nom}}\ (Mechanical\ losses) \tag{5.19}$$

$$n_{eng,mech} = \frac{M_{eng}}{M_{eng,noloss}}\ (Mechanical\ efficiency\ of\ engine) \tag{5.20}$$

$$P_{eng} = M_{eng} \cdot n_{eng} \cdot 2 \cdot \pi [W]\ (Engine\ brake\ power) \tag{5.21}$$

### 5.1.6. Turbocharger

The turbocharger module calculates the inlet receiver pressure using which the inlet condition of the cylinder will be calculated. The turbocharger system is modelled using following equations: [36]

$$\pi_{com} = (1 + \beta \cdot \delta \cdot \chi \cdot \eta_{TC} \cdot \tau_{TC} \cdot (1 - \frac{1}{\pi_{tur}(\frac{\gamma_{gas}-1}{\gamma_{gas}})}))^{(}\frac{\gamma_{air}}{\gamma_{air}-1})(Compressor\ pressureratio) \tag{5.22}$$

$$\psi = \frac{c_{p,gas}}{c_{p,air}}(Ratio\ of\ specific\ heat\ of\ gas\ and\ air) \tag{5.23}$$

$$p_b = \pi_{com} \cdot p_a = \pi_{com} \cdot p_{amb}\ \ [Pa](Theoretical\ Pressure\ after\ compressor) \tag{5.24}$$

$$p_{ir} = \int \frac{p_b - p_{ir}}{\tau_{TC,time}} dt + p_{ir,0}\ [Pa]\ (Inlet\ receiver\ pressure) \tag{5.25}$$

$$\eta_{TC} = f(p_{ir})\ (Turbocharger\ \ efficiency) \tag{5.26}$$

### 5.1.7. Waste gate

The waste gate controls the maximum air pressure in diesel engines and the air fuel ratio in gas engines. Waste gate allows integration of smaller turbocharger with a diesel engine for better performance at part load condition. This however limits its use at high loads to prevent high inlet receiver pressure. The waste gate also controls the excess air in gas engine which significantly affects the combustion speed and process of gas. The waste gate uses a PI (proportional integrator) controller with an anti wind-up gain.

### 5.1.8. Fuel supply control

The engine is controlled by the amount of fuel entering the cylinder. The engine control contains fuel supply system that controls the amount of fuel. The fuel supply system expresses diesel as pilot and main fuel along with gas fuel is expressed in terms of controller position $(X_{f,d}, X_{f,g} and X_{f,p})$ [33]

$$m_{f,d} = m_{f,d,nom} \cdot X_{f,d}[\frac{kg}{cyl \cdot cyc}](Diesel\ fuel\ mass\ injected\ per\ cylinder\ per\ cycle) \tag{5.27}$$

$$m_{f,g} = m_{f,g,nom} \cdot X_{f,g}[\frac{kg}{cyl \cdot cyc}](Gas\ fuel\ mass\ injected\ per\ cylinder\ per\ cycle) \tag{5.28}$$

$$m_{f,p} = m_{f,p,nom} \cdot X_{f,p}[\frac{kg}{cyl \cdot cyc}](Pilot\ fuel\ mass\ injected\ per\ cylinder\ per\ cycle) \tag{5.29}$$

### 5.1.9. Engine control system

The engine control system controls the speed of the engine to the pre defined set speed during the operation by controlling the fuel injection. The controller positions ($X_{f,d}, X_{f,g}, X_{f,p}$) are controlled are controlled by this system block. This system consists of three main controllers:

- Gas fuel controller
- Diesel fuel controller
- Pilot fuel controller

## 5.2. Rotational dynamics

This block is modelled based on Newtons second law of rotation. By measuring the difference of torque from consumer and the source and using the known inertia values revolutions of shaft can be calculated. For engine the rotation speed is calculated as follows [37]:

$$n_{eng} = \int \frac{1}{2\pi} \cdot \frac{M_{eng} - M_{load}}{I_{tot}} \cdot dt + n_o \tag{5.30}$$

Where,
$I_{tot}$= Total inertia of shaft and load under consideration; $n_o$ = initial shaft rotation speed

## 5.3. Verification of engine model

The gas engine model is verified with data available from Wartsila W12V34DF engine running under the diesel mode for different loading condition. The verification is made based on the specific fuel consumption obtained from the model and from the data available from Wartsila.

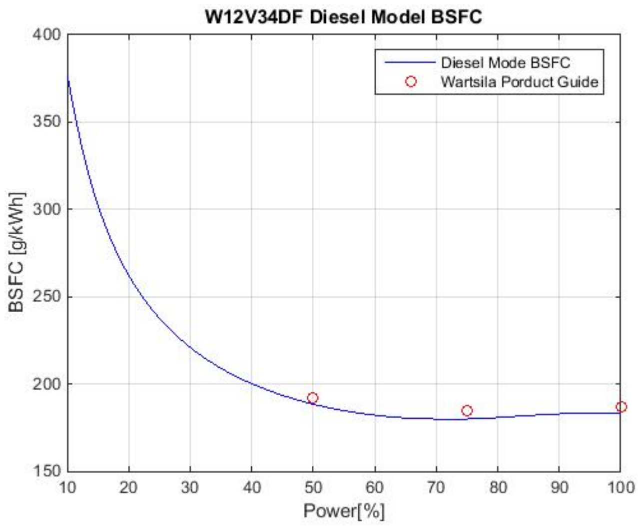



Figure 5.5: Wartsila W12V34DF Break specific fuel consumption (BSFC)

## 5.4. Emission

This block is modelled to give the amount of emission on the basis of fuel consumption.

### 5.4.1. $CO_2$

The emission of $CO_2$ is proportional to fuel oil consumption. The emission rate based on specific fuel consumption can be given as: [38]

Table 5.1: Fuel based $CO_2$ emission

| **Type of Fuel** | **$CO_2$ emission** |
|---|---|
| Heavy Fuel Oil (HFO) | 3.114 gm/gm oil |
| Light fuel Oik (LFO) | 3.151 gm/gm oil |
| Diesel Oil/ Gas Oil (DO/GO) | 3.206 gm/gm oil |
| Liquified Natural Gas (LNG) | 2.750 gm/gm gas |
| Liquefied Natural Gas with DO as pilot fuel | 2.780 gm/gm gas |

### 5.4.2. $SO_2(SO_x)$

The amount of $SO_2$ is proportional to content of sulphur present in the oil given as: $21 * \%S$ kg per ton of fuel oil.[39] Here %S is the percentage of sulphur present in the fuel oil. In natural gas there no sulphur content present. Mass fraction of sulphur for different fuel types is given below: [38]

Table 5.2: Fuel based $SO_2$ emission

| **Type of Fuel** | **% S** |
|---|---|
| Heavy fuel oil (HFO) | 0.03 |
| Marine diesel fuel(MDF) | 0.005 |
| Natural fuel gas | 0.02 |

### 5.4.3. Particulate matter(PM)

The emission of particulate matter is affected by the sulphur content present in the fuel. The particulate emission factor in g/kWh = 0.26 + 0.081 $\cdot S$ + 0.103 $\cdot$ $S^2$. Since there is no sulphur content in natural gas the particulate emission from gas engine is practically zero. [40]

## 5.5. Electrical machines

Introduction of reference frames in modelling of electrical machines is useful for their analysis and also provides powerful tool for implementing control techniques. This reference frame theory is developed from the breakthrough analysis of three-phase ac machines. It is now possible to transform the phase variable machine description into another reference frame. This transformation allows to simplify the complex mathematical machine models. The control techniques are based on the current, torque and flux of of such machines.

### 5.5.1. Per unit representation

The per unit representation simplifies the complex analysis by setting a common set base parameters. The per unit representation of any quantity is: [41]

$$Qunatity(perunit) = \frac{Quantity\ (normal\ units)}{Base\ value\ (normal\ units)} \tag{5.31}$$

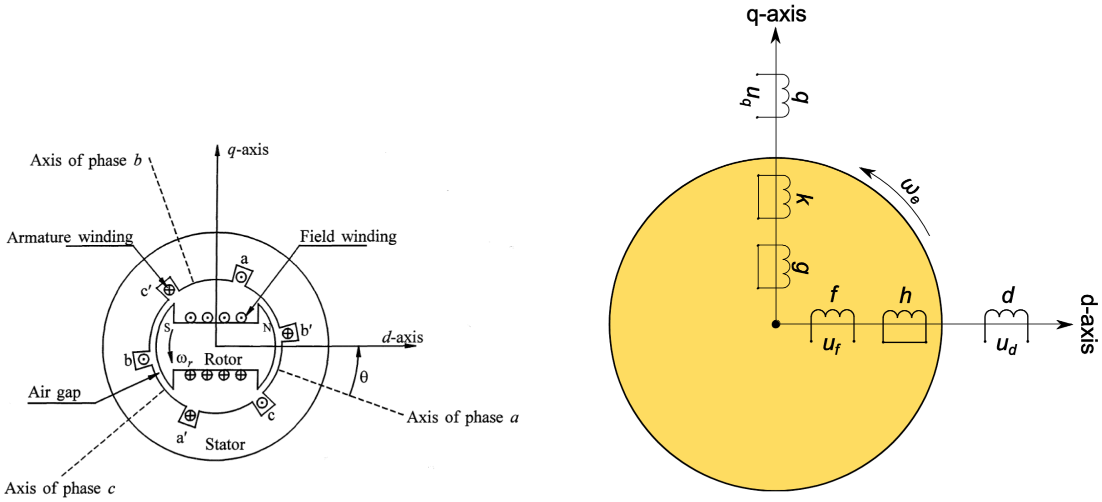
The base value for per unit conversions are given in following table:

Table 5.3: Per unit representation of electrical machine's parameters

| **Base Values** | | |
|---|---|---|
| $S_b$ | $S_{nom}$ | $V \cdot A$ |
| $U_b$ | $U_{nom}$ | V |
| $\omega_{eB}$ | $2\pi f_{nom}$ | $rad \cdot s^{-1}$ |
| $I_B$ | $\frac{S_B}{U_B}$ | A |
| $Z_B$ | $\frac{U_B}{I_B}$ | $\omega$ |
| $\omega_{eB}$ | $\frac{2}{p}\omega_{eB}$ | $rad \cdot s^{-1}$ |
| $\psi_B$ | $\frac{U_B}{\omega_{eB}}$ | $V \cdot S$ |
| $L_B$ | $\frac{Z_B}{\omega_{eB}}$ | H |
| $\tau_B$ | $\frac{S_B}{\omega_{mB}}$ | $N \cdot m$ |

### 5.5.2. Synchronous generator

The generator model is developed based on the synchronous machine model. It is based on the dq- reference frame consisting of three dampers, with two on q-axis and one on d-axis. [42]




(a) Schematic representation of synchronous machine

(b) Stator representation in dq reference frame

Figure 5.6: Synchronous machine

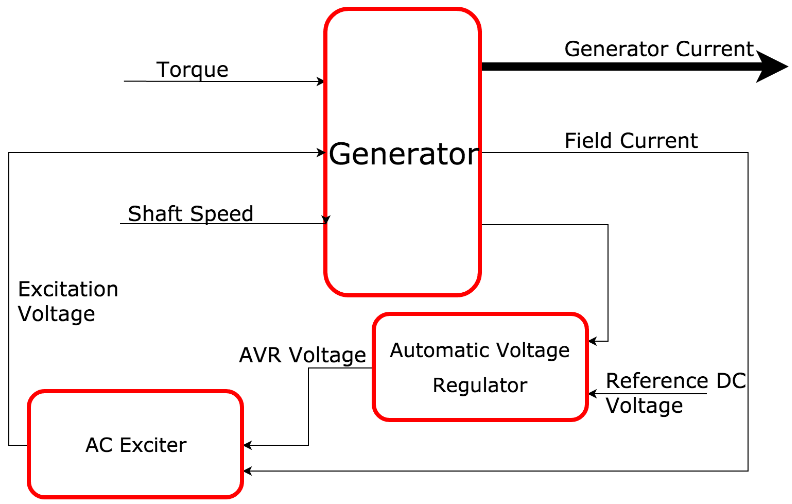



Figure 5.7: Generator model overview

The equivalent circuit for modelling each axis of the generator is shown below. The only difference between circuits is the field winding with source $u_{fd}$. This field winding on the d-axis enables the generator to control the magnetization of rotor. [42]

#### Modelling of stator

For modelling the stator two situations are considered i.e one with the stator dynamics and one without stator dynamics.

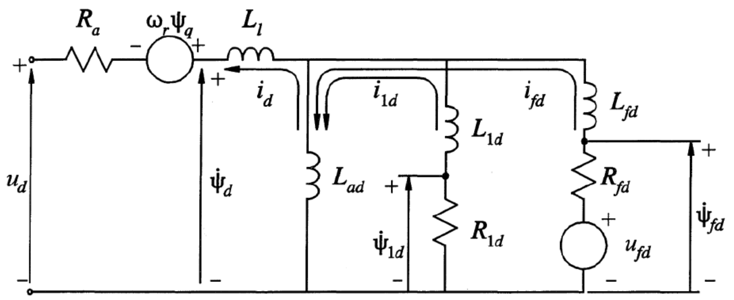



Figure 5.8: d-axis equivalent circuit [42]

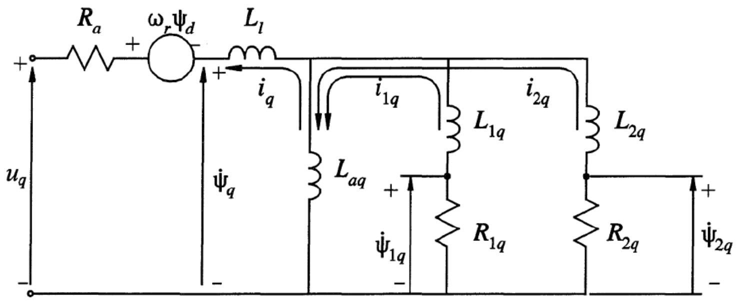



Figure 5.9: q-axis equivalent circuit [42]

## Voltage equation with stator dynamics

The voltage equation of generator considering the stator dynamics can be summarized in following equations:

$$\frac{d}{dt}\begin{bmatrix}\psi_d\\\psi_q\\\psi_{fd}\\\psi_{1d}\\\psi_{1q}\\\psi_{2q}\end{bmatrix}=\begin{bmatrix}0&-\omega_r&0&0&0&0\\-\omega_r&0&0&0&0&0\\0&0&0&0&0&0\\0&0&0&0&0&0\\0&0&0&0&0&0\\0&0&0&0&0&0\end{bmatrix}\begin{bmatrix}\psi_d\\\psi_q\\\psi_{fd}\\\psi_{1d}\\\psi_{1q}\\\psi_{2q}\end{bmatrix}+\begin{bmatrix}r_a&0&0&0&0&0\\0&r_a&0&0&0&0\\0&0&-r_{fd}&0&0&0\\0&0&0&-r_{1d}&0&0\\0&0&0&-r_{1q}&0&0\\0&0&0&0&0&-r_{2q}\end{bmatrix}\begin{bmatrix}i_d\\i_q\\i_{fd}\\i_{1d}\\i_{1q}\\i_{2q}\end{bmatrix}+\omega_{eB}\begin{bmatrix}1&0\\0&1\\0&0\\0&0\\0&0\\0&0\end{bmatrix}\begin{bmatrix}u_d\\u_q\end{bmatrix}+\omega_{eB}\begin{bmatrix}0\\0\\0\\1\\0\\0\end{bmatrix}u_{fd} \tag{5.32}$$

The dynamic flux equation independent of winding currents can be written as:

$$\frac{d}{dt}\vec{\psi}_g=(A_g(\omega_r)+\omega_{eB}R_gL_g^{-1})\vec{\psi}_g+\omega_{eB}S_gu_g+\omega_{eB}B_gu_{fd} \tag{5.33}$$

## Torque equations with stator dynamics

The electrical torque inside a synchronous generator is dependent on the power transfer through the air gap. The torque on the shaft of the synchronous machine given by the prime mover (e.g Gas engine)is given as: [43]

$$\tau_g=\tau_B(\psi_d i_q-\psi_q i_d)+K_D\omega_{shaft} \tag{5.34}$$

Where,
$K_D$ = Viscous damping, $\omega_{shaft}$ = Mechanical speed

From the above equation the shaft dynamics can be expressed as:

$$\frac{d}{dt}\omega_{shaft}=\frac{1}{J_{g+J_{de}}}\left(\tau_{de}-\tau_g\right)=\frac{2}{p}\frac{d}{dt}\omega_r \tag{5.35}$$

Where,
$J_g$ = Inertia of Generator Shaft, $J_{de}$= Inertia of Engine Shaft

The relation between the mechanical speed ($\omega_{shaft}$) and the electrical speed ($\omega_r$) are dependent on the number of poles pairs (p/2) in the rotor.

Voltage equation without Stator Dynamics

During modelling of synchronous machine without stator dynamics, the dynamic fluxes ($\dot{\psi}_d, \dot{\psi}_q$) are considered zero. Thus stator is no longer dynamic and is modelled on a constant value. The state space equation for flux dynamics is as follows:

$$\frac{d}{dt}\begin{bmatrix}\psi_{fd}\\ \psi_{1d}\\ \psi_{1q}\\ \psi_{2q}\end{bmatrix} = \omega_{eB}\begin{bmatrix}\frac{r_{fd}}{l_{fd}} & 0 & 0 & 0\\ 0 & \frac{r_{1d}}{l_{1d}} & 0 & 0\\ 0 & 0 & \frac{r_{1q}}{l_{1q}} & 0\\ 0 & 0 & 0 & \frac{r_{2q}}{l_{2q}}\end{bmatrix}\begin{bmatrix}\psi_{fd}\\ \psi_{1d}\\ \psi_{1q}\\ \psi_{2q}\end{bmatrix} + \omega_{eB}\begin{bmatrix}0 & 0 & \frac{r_{fd}}{l_{fd}}l_{ad} & 0\\ 0 & 0 & \frac{r_{1d}}{l_{1d}}l_{ad} & 0\\ 0 & 0 & 0 & \frac{r_{1q}}{l_{1q}}l_{aq}\\ 0 & 0 & 0 & \frac{r_{2q}}{l_{2q}}l_{aq}\end{bmatrix}\begin{bmatrix}i_d\\ i_q\\ i_ad\\ i_aq\end{bmatrix} + \omega_{eB}\begin{bmatrix}1\\0\\0\\0\end{bmatrix}u_{fd} \quad (5.36)$$

The dynamic flux equation independent of current is given as below:

$$\frac{d}{dt}\psi_g = \left(\omega_{eB}A_g + \omega_{eB}R_g L_g^{-1}F_g\right)\vec{\psi_g} + \omega_{eB}R_g L_g^{-1}S_g\vec{u_g} + \omega_{eB}B_g u_{fd} \quad (5.37)$$

Torque equations without stator dynamics

The torque on the shaft of the synchronous machine can be given as:

$$\tau_g = \tau_B(l_{ad}i_{ad}i_q - l_{aq}i_{aq}i_d) - K_D\omega_{shaft} \quad (5.38)$$

The shaft dynamics is given as:

$$\frac{d}{dt}\omega_{shaft} = \frac{1}{J_{g+J_{de}}}\left(\tau_{de} - \tau_g\right) = \frac{2}{p}\frac{d}{dt}\omega_r \quad (5.39)$$

Power angle

When synchronous machine is rotating at same frequency as the AC signal frequency it is connected then there is no net power produced by the generator. The phase angle difference between both the frequency makes the machine to deliver the power. This angle is defined as torque or the power angle. [42]

$$\frac{d}{dt}\delta_g = \omega_r - \omega_e \quad (5.40)$$

Terminal voltage and current can be defined in terms of power angle as follows:

$$u_g = \begin{bmatrix}\sin\delta_g & -\cos\delta_g\\ \cos\delta_g & \sin\delta_g\end{bmatrix}u_{net} \quad (5.41)$$

$$I_g = D_g I_{net} \quad (5.42)$$

When the power angle is zero i.e machine is in phase with the network frequency then the transformation matrix switches the real and imaginary parts of $\vec{I_g}$

$$D_g^{-1} = D_g^T = \begin{bmatrix}\sin\delta_g & \cos\delta_g\\ -\cos\delta_g & \sin\delta_g\end{bmatrix} \quad (5.43)$$

### 5.5.3. Automatic voltage regulator

This regulator controls the input signal to a level there by forming appropriate control for the exciter. It contains both regulating and excitation system stabilizing the DC voltage. The complete voltage regulator and excitation is given below:

### 5.5.4. AC exciter

The excitation system is used to provide direct current to the field winding of the synchronous machine. It also controls the performance of the power system by controlling the filed voltage which in turn controls the field current.

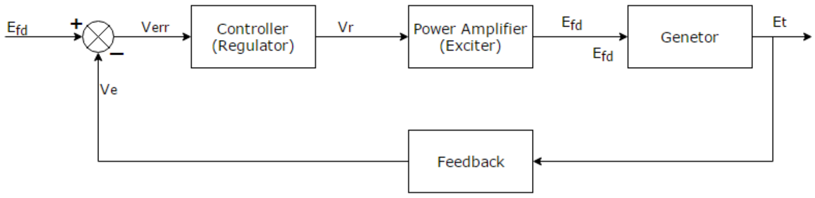



Figure 5.10: Excitation control system

### Influence of different excitation voltages

In figure 5.11 influence of different excitation voltages is visualized for fixed rotational speed at 78.5 rotatation per second (rps). The terminal current linearly increases with the excitation voltage which is used to check whether the model is able to increase the output with increased grid voltage.

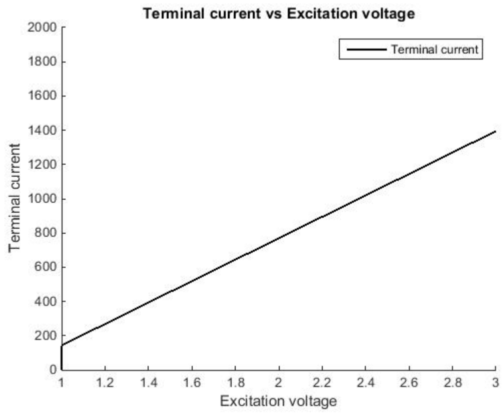
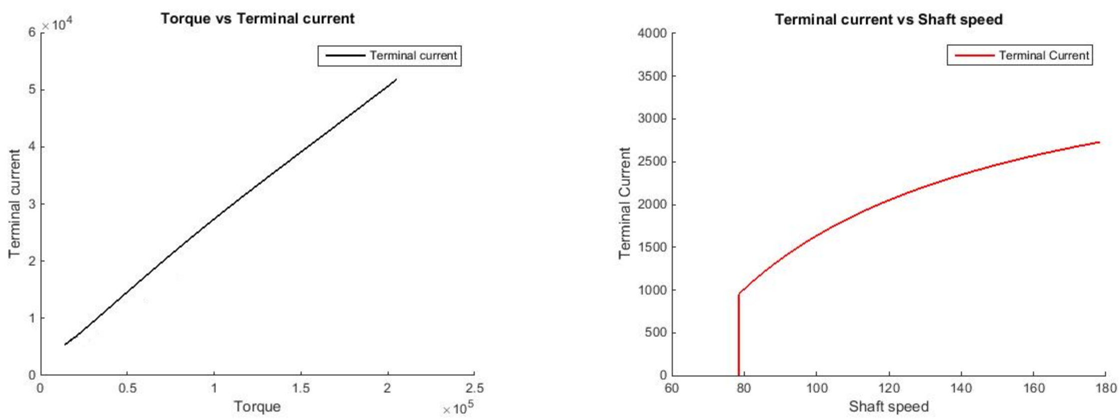



Figure 5.11: Generator excitation voltage vs terminal current

### Terminal current relation

Figure 5.12 shows the torque and terminal current of the generator with constant load and increasing excitation voltage. As can be seen from the figure 5.12a torque increases quadratic with terminal current with a significant slope. Figure 5.12b shows how output current increases linearly with increased shaft speed. This is due to increase in reactance because of increased shaft frequency. This is used to determine the output torque to the rotational dynamics and voltage characteristics of the synchronous generator.




(a) Torque characteristics

(b) Shaft speed characteristics

Figure 5.12: Generator characteristics

### 5.5.5. Verification of generator model

The model is verified by comparing the power of the generator to the performance data available from Caterpillar for C280-8 [44]. The comparison is made in terms of efficiency through varying power requirements as shown in figure 5.13. As seen the generator is running as approximate efficiency of 95.86% which is approximately equal to 96% available form the data sheet.

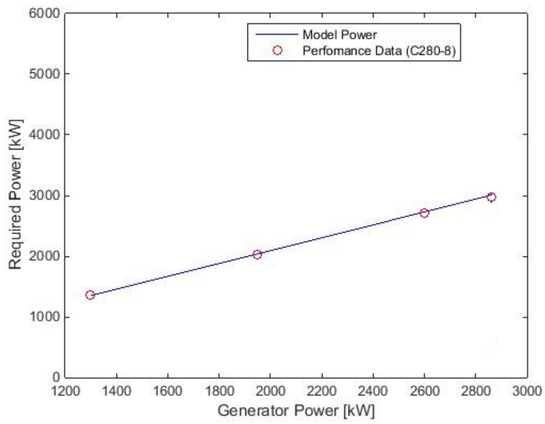



Figure 5.13: Comparision between model power and data sheet

### 5.5.6. Induction motor

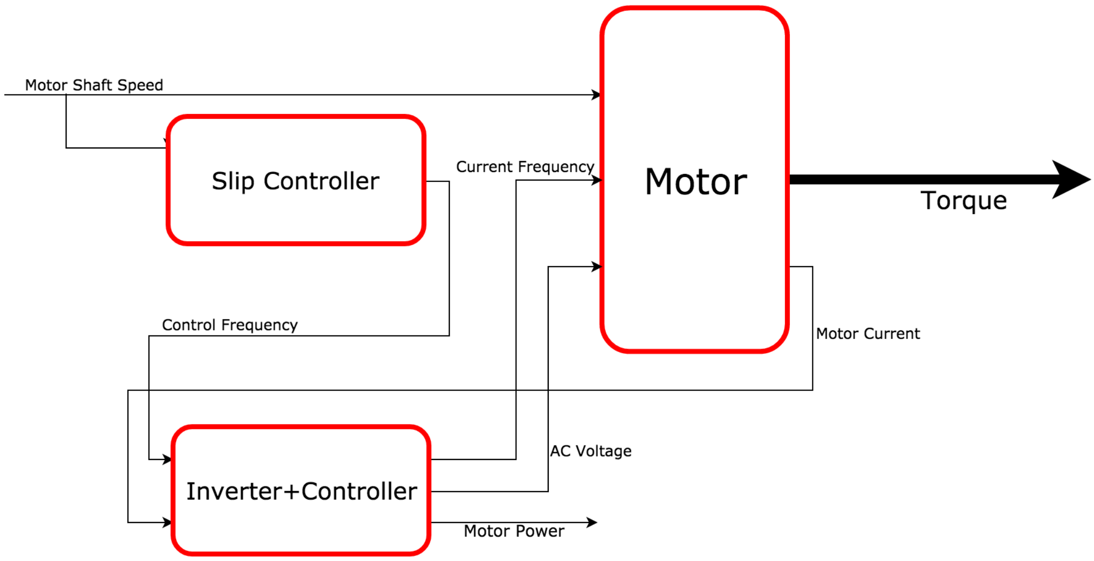



Figure 5.14: Motor model overview

The small difference between the induction machine and synchronous machine is that the induction machine has no external source of excitation circuit for the rotor windings because of the shorted rotor windings. The rotor windings are closed circuit resulting in shorted circuit. The flux is generated inside the rotor because of the electrical frequency difference between the rotor and the stator. Figure 5.15 and 5.16 shows the equivalent circuit of induction machine.[42]

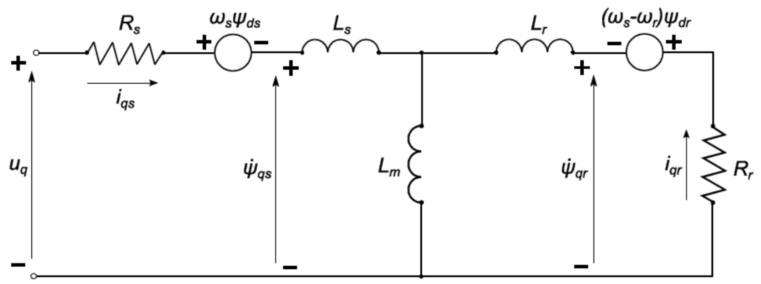



Figure 5.15: d-axis equivalent circuit

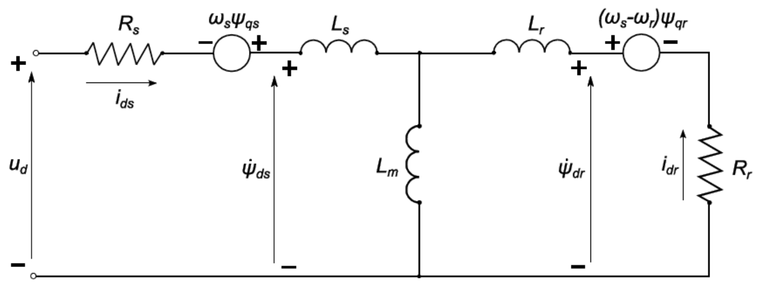



Figure 5.16: q-axis equivalent circuit

### Voltage equation with stator dynamics

With stator flux dynamics $(\dot\psi_d, \dot\psi_q)$ into consideration the state space equation for the flux dynamics can be given as follows:

$$\frac{d}{dt}\begin{bmatrix}\psi_{ds}\\ \psi_{qs}\\ \psi_{dr}\\ \psi_{qr}\end{bmatrix} = \begin{bmatrix}0 & \omega_s & 0 & 0\\ -\omega_s & 0 & 0 & 0\\ 0 & 0 & 0 & (\omega_s-\omega_r)\\ 0 & 0 & -(\omega_s-\omega_r) & 0\end{bmatrix}\begin{bmatrix}\psi_{ds}\\ \psi_{qs}\\ \psi_{dr}\\ \psi_{qr}\end{bmatrix} + \omega_{eB}\begin{bmatrix}-r_s & 0 & 0 & 0\\ 0 & -r_s & 0 & 0\\ 0 & 0 & -r_r & 0\\ 0 & 0 & 0 & -r_r\end{bmatrix}\begin{bmatrix}i_ds\\ i_qs\\ i_dr\\ i_qr\end{bmatrix} + \omega_{eB}\begin{bmatrix}1 & 0\\ 0 & 1\\ 0 & 0\\ 0 & 0\end{bmatrix}\begin{bmatrix}u_{ds}\\ u_{qs}\end{bmatrix} \tag{5.44}$$

Flux dynamics can be represented independent of current as follows:

$$\frac{d}{dt}\psi_m = \left(A_m + \omega_{eB}R_m L_m^{-1}\right)\psi_m + \omega_{eB}S_m u_m \tag{5.45}$$

### Torque equations with stator dynamics

The electrical torque developed by the induction machine is dependent on the power transferred across the air-gap. The torque on shaft of the inductor machine is given as: [45]

$$\tau_m = \frac{\tau_B\left(\psi_{dr}i_{qs} - \psi_{qr}i_{ds}\right)l_m}{l_m + l_r} - K_D\omega_{shaft} \tag{5.46}$$

$$\frac{d}{dt}\omega_{shaft} = \frac{1}{J_m + J_t}(\tau_m - \tau_t) = \frac{2}{p}\frac{d}{dt}\omega_r \tag{5.47}$$

### Voltage equation without stator dynamics

When neglecting the stator flux dynamics $(\dot\psi_d, \dot\psi_q)$ the state space equation of induction machine is given as:

$$\frac{d}{dt}\begin{bmatrix}\psi_{dr}\\ \psi_{qr}\end{bmatrix} = \begin{bmatrix}-\omega_{eB}\frac{r_r}{l_r} & (\omega_s-\omega_r)\\ -(\omega_s-\omega_r) & -\omega_{eB}\frac{r_r}{l_r}\end{bmatrix}\begin{bmatrix}\psi_{dr}\\ \psi_{qr}\end{bmatrix} + \omega_{eB}\begin{bmatrix}r_r\frac{l_h}{l_r} & 0\\ 0 & r_r\frac{l_h}{l_r}\end{bmatrix}\begin{bmatrix}i_{ds}\\ i_{qs}\end{bmatrix} \tag{5.48}$$

The flux equation independent of stator current is given as:

$$\frac{d}{dt}\vec{\psi_m} = \left(A_m + \omega_{eB}R_m L_m^{-1}F_m\right)\vec{\psi_m} + \omega_{eB}R_m L_m^{-1}S_m\vec{u_m} \tag{5.49}$$

### Motor dynamics

Figure 5.17 shows a typical torque shaft-speed relation at constant frequency and voltage. This is used to understand the output of motor which is used to determine the output characteristic of motor to match the desired load given to the motor through rotational dynamics.

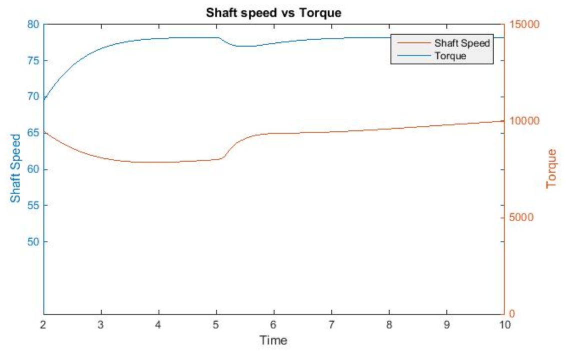



Figure 5.17: Motor shaft speed and torque relation

## 5.5.7. Slip controller

This is speed controller for the motor by controlling the frequency of input AC signal. It is modelled using generic propotional-integral (PI) controller.

## 5.5.8. Verification of motor model

Motor model is verified based on efficiency at different output power. Figure 5.18 shows graph of input power v/s output power with efficiency of approximately 95%.

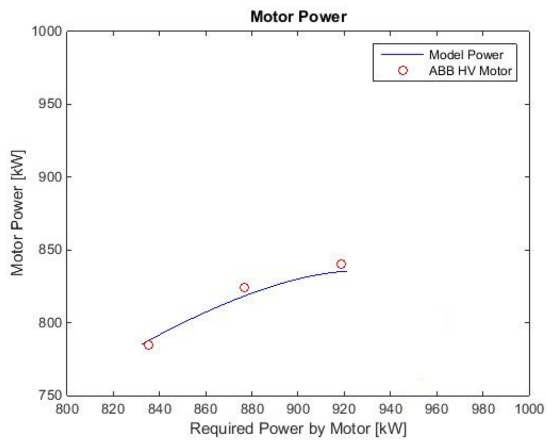



Figure 5.18: Motor input and output power

# 5.6. DC bus

The DC bus is modelled on the dynamic capacitor model with capacitor ensuring stability of the DC voltage. The model overview of the DC bus with the rectifier and converter is given below:

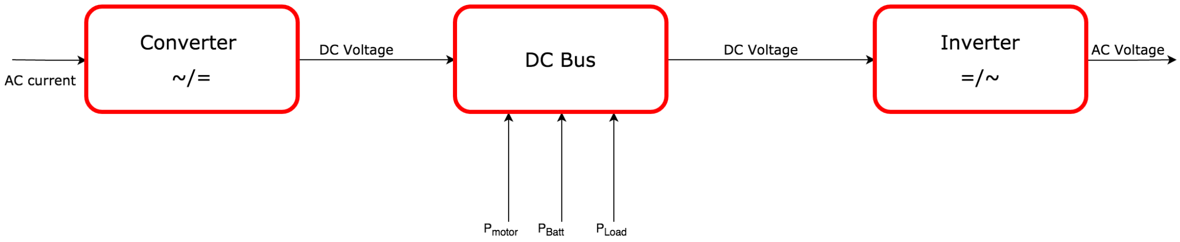



Figure 5.19: DC bus model overview

This is also referred to as voltage source conveter (VSC) based high voltage direct transmission (HVDC). They use insulated gate bipolar transistors under controlled manner. This system operates at high switching frequency based on pulse width modultation (PWM)

The sending and receiving end of a VSC system is similar with one operating as rectifier and another as inverter. The dc side contains capacitors. The size of the capacitor depends on the required DC voltage.[46] The prime objective of capacitor is to provide the low inductance path for turned of current and energy storage to control the power flow. The inverter side of DC link controls the active power while the rectifier side controls the DC voltage. In the DC bus there is chopper resistance to dissipate the initial power during the start-up of the motor or other electrical load on-board the ship. The circuit diagram of DC bus is given in figure 5.20.

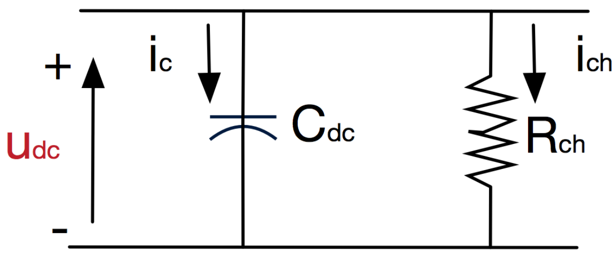



Figure 5.20: DC bus circuit diagram

A basic assumption is made that the DC circuit is assumed to be well protected. Converters and rectifiers in the DC grid are considered to be working at maximum efficiency.Connection between different electrical components is through the cables considered as wired with no efficiency loss and full insulation.Complexity of DC circuit breakers is not considered and are assumed to be easily integrated and easy to use.

### Capacitor configuration of DC distribution

Capacitors store energy by piling up the positive and negative charges on plate that are separated by insulating dielectric. The capacitance depends on the permittivity of the dielectric($\epsilon$) and area of the plates (A) and distance between the plates(d).

$$q = CV \tag{5.50}$$

$$C = \frac{\epsilon A}{d} \tag{5.51}$$

The model for dc link can be given by following characteristic equation:

$$\frac{CU_{dc}}{dt} = i_{dc} - i_L \tag{5.52}$$

Where,
$i_{dc} = dclinkcurrent$, $i_L = \frac{U_{dc}}{R_L}$, $R_L$ = load resistance

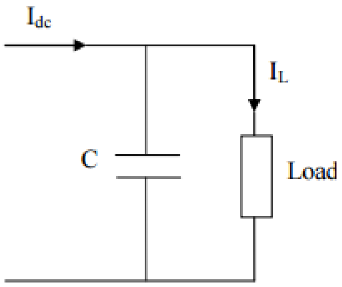



Figure 5.21: DC link model [46]

The equivalent DC link model is given in following figure:

The dynamic capacitor equation in d-q reference frame is given as:

$$\frac{d}{dt}\begin{bmatrix} u_{d,dc} \\ u_{q,dc} \end{bmatrix} = \frac{1}{C_{dc}}(-I_{net} - I_{ch} - I_{inv}) \tag{5.53}$$

$$= \frac{1}{C_{dc}}\left(-\begin{bmatrix} i_{d,net} \\ i_{q,net} \end{bmatrix} - \begin{bmatrix} u_{d,dc} \\ u_{q,dc} \end{bmatrix}\frac{1}{R_{ch}} - \begin{bmatrix} u_{d,dc} & u_{q,dc} \\ u_{d,dc} & -u_{d,dc} \end{bmatrix}^{-1}\begin{bmatrix} P_{inv} \\ 0 \end{bmatrix}\right) \tag{5.54}$$

$$= \frac{1}{C_{dc}}\left(-I_{net} - \frac{1}{R_{ch}}u_{dc} - \frac{u_m I_m}{||u_{dc}||_2^2}u_{dc}\right) \tag{5.55}$$

For adding a source or a consumer to the DC bus possible by adding the extra power term of that respective component. The overall control strategy of DC transmission is given in following figure:

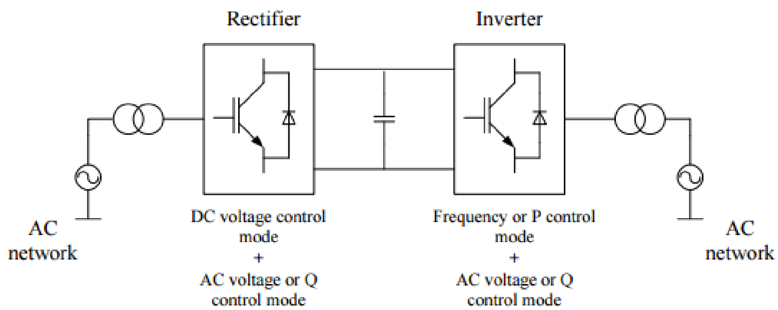



Figure 5.22: Control structure of DC transmission [46]

The inverter side controls the active power and the rectifier side controls the DC voltage.

### Operation of VSC DC link

The system is based on PWM technique. PWM generates pulse width modulated signals by comparing the magnitude of instantaneous triangular waveform with the sinusoidal input reference. Thus system can generate its own voltage waveform independent of the ac system. PWM averages the output voltage and controls the value for short periods called as switching period. The control of active and reactive power is based on the PWM template which can be changed instantaneously.

### DC voltage control

The DC voltage is controlled using classic control algorithm that is based on the transfer function between the DC link voltage and the reference current value. the power balance equation is given by:

$$P_{ac} + P_{dc} + P_{cap} = 0 \tag{5.56}$$

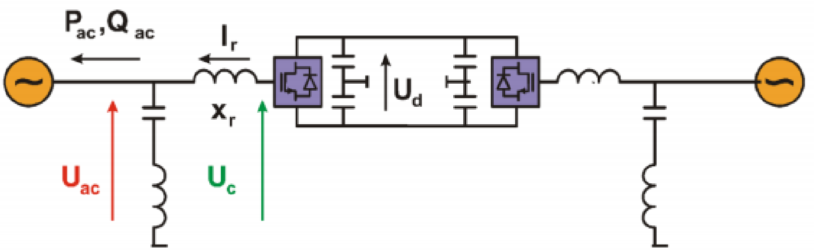



Figure 5.23: Single line diagram of VSC control system [47]

$$\frac{3}{2}V_d i_d + V_{dc} i_{cap} + V_{dc} I_d c = 0 \tag{5.57}$$

Where, $I_{dc}$ and $I_{cap}$ are DC bus and capacitor currents respectively. Here the $\frac{3}{2}$ is from the Park's transformation [41]. From above equation, the capacitor current is given by:

$$i_{cap} = -(\frac{3V_d i_d}{2V_{dc}} + I_{dc}) \tag{5.58}$$

The above equation on further simplification gives equation 5.52

### 5.6.1. Converter

The converter in the DC distribution have very important role that is to eliminate the tight frequency regulations of the AC signals and convert them into DC. The main function of rectifier is to convert the AC voltage into DC voltage.

The pulse width modulation technique implemented in AC-DC converters has significant aspects. This helps in stabilizing the output DC voltage with less harmonics in voltage.This hence improves power system stability. Hence AC-DC converters are modelled on space vector pulse width modulation (SVPWM) using d-q reference frame.

As the control of system voltage is performed by the generator excitation circuit the AC-DC conversion rectifiers can be of non-controlled type with the use of passive diodes. The model overview of converter is given below:

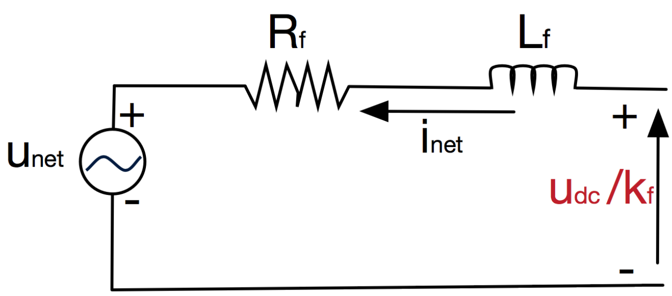



Figure 5.24: Rectifier model

The converter converts the AC voltage into DC voltage with factor $k_f$. It is modelled on the rectification equation given as:

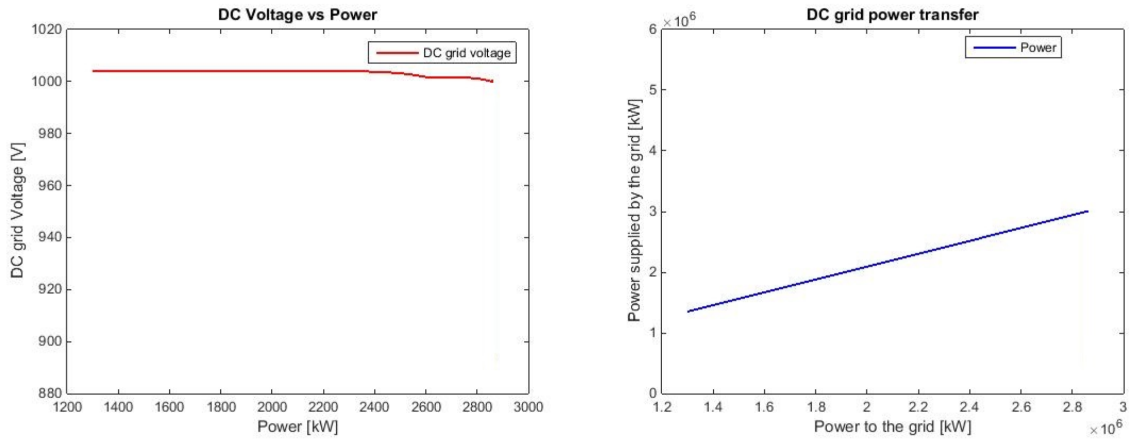
$$\vec{I_{net}} = \frac{1}{k_f} \begin{bmatrix} R_f & -L_f\omega_{net} \\ L_f\omega_{net} & R_f \end{bmatrix}^{-1} \vec{u_{dc}} + \begin{bmatrix} -R_f & L_f\omega_{net} \\ L_f\omega_{net} & -R_f \end{bmatrix}^{-1} \vec{u_{dc}} \tag{5.59}$$

### 5.6.2. Inverter

The inverter performs a significant role in the DC distribution circuit. Its role is opposite to that of converter that is converting DC voltage into AC voltage. The AC voltage produced from inverter is regulated as DC voltage which is regulated by the converter during its conversion. It is accompanied with an inverter controller to control the AC signal amplitude by providing a set point so it can also be called as a flux controller for a motor. The produced AC signal is further sent to the motor in form of AC voltage.

### 5.6.3. Verification of DC bus model

The DC grid is modelled with zero transmission loss so it will be verified if it is able to transport the power in terms of DC voltage with zero transmission loss. The DC grid is modelled for 1000V. Figure 5.25a shows DC grid voltage measured with varying power to show that, irrespective of the power the grid voltage approximately remains constant at 1000V. In one comparison the power transferred by the grid is measured as shown in figure 5.25b with zero transmission loss. As it is a constant voltage grid the grid voltage should remain constant irrespective of power.




(a) DC bus voltage with respect to Power

(b) DC bus efficiency

Figure 5.25: DC grid performance characteristics

## 5.7. Lithium ion battery

This section explains the modelling of lithium ion battery and control of power from the battery during its charging and discharging process. The model developed is based on the lead acid model of Stapersma [48] and thesis of Verluijs [49] and lithium ion (LI) developed by F. Jacobs. [11]The battery is modelled based on the figure 5.26.

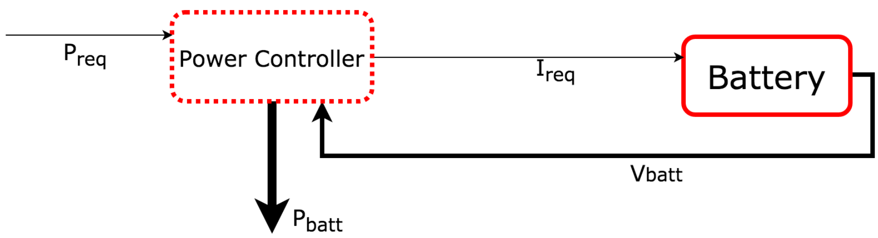



Figure 5.26: Battery model overview

For higher voltage and energy capacity batteries are often connected in series or parallel connection. In parallel connection of the battery the capacity of battery increases and in series connection the voltage increases. Higher voltage is beneficial as it will result in lower current which is beneficial to lower electrical losses and temperature losses.

The battery converts electrical energy into chemical energy during charging and vice versa during the discharge. The battery is modelled in matlab based on lead-acid model. Discharge process is based on the positive current flowing through the battery and charging is associated with negative current. The voltage of battery is dependent on the state of charge (SOC), temperature, internal resistance and capacity. At constant charging and discharge current the voltage is not constant and hence voltage dynamics have to be considered. The battery is based on the power requirement model. This means from the operation profile the power requirement of motor will be calculated and based on the power supplied by the DC distribution system difference in power between above two can be supplied or consumed by the battery. An output voltage will be produced based on the type of battery which combined with the battery current gives the power delivered by the battery. This delivered power will be feedback to the operation profile power after which the current will be changed accordingly to produce the required power.

Battery is modelled on four main equations based on the characteristics of the battery:

- Capacity Equation
- State of discharge equation
- Open Cell voltage equation
- Internal resistance equation

### 5.7.1. Capacity of battery

The capacity of the battery is defined as the amount of energy stored inside the battery. This is the maximum amount of energy that can be supplied by the battery. There are two types of capacity:

- $C_t(I)[Ah]$, instantaneous capacity dependent on current drawn from the battery.
- $C_1[Ah]$, theoretical maximum capacity at infinitesimal discharge current

Here $C_\infty$ is the input for the model.

From the capacity equation the variables can be defined as: x gives the state of charge(SOC), y is the pseudo-discharge state and $x_{end}$ is the discharge factor.

$$x_{end} = discharge\ factor = \frac{instantaneous\ capacity}{maximum\ capacity} \tag{5.60}$$

$$x_{end} = \frac{x}{y} = \frac{C_t(I)}{C_\infty} \tag{5.61}$$

### 5.7.2. C rating

The C rating is used to indicate the discharge current of a battery. The C rating gives a forecast of how long can a battery be charged or discharged based on certain constant current. It is defined as:

$$C_r = IC_n \tag{5.62}$$

### 5.7.3. Coefficients

To calculate the capacity some coefficients have to be defined there by calculating battery characteristics for different battery types. For current application Valance data sheet parameters are used for modelling the Lithium Polymer Battery (LMP) battery. Four main coefficients are defines as follows:

- $\alpha$ shaping the minimum value of instantaneous capacity ($C_t(I)$)
- $\beta$ is defined as the 5 hour fraction of the total infinite discharge capacity

- $\tau$ is defined as the characteristic discharge time hour
- $\tau_{char}$ is the characteristic discharge time in hour for 5 hour discharge fraction

$$\alpha = \frac{W_{cell} \cdot c_0}{W_{cell} \cdot c_\infty} \tag{5.63}$$

$$\beta = \frac{W_{cell} \cdot c_5}{W_{cell} \cdot c_\infty} \tag{5.64}$$

$$\tau_{char} = \frac{1-\alpha}{\beta-\alpha} \tag{5.65}$$

$$\tau = t_5 \cdot ln(\tau_{char}) \tag{5.66}$$

### 5.7.4. State of charge

The real discharge state x, is know as state of charge (SOC). This means that when x is 1 the battery is completely discharge and when the value of x is 0 the battery is fully charged. State of charge and state of discharge are defined by following equation:

$$1 - x_d = SOC \tag{5.67}$$

$$1 - SOC = SOD = x_d \tag{5.68}$$

State of discharge can be expressed in terms of infinite capacity and current as:

$$x = \frac{Q}{C_\infty} \tag{5.69}$$

From state of discharge (x) the value of pseudo state of discharge (y) can be calculated. The value of y determines if battery can be discharged with given amount of current. When the value of y is 1 it means that the battery cannot be further discharged with given current value. This current value must decrease to further discharge the battery there by bringing down the value of y. During charging and discharging x and y are related as follows:

$$x_{end} = \frac{x_d}{y_d} = \frac{C_t}{C_\infty} \tag{5.70}$$

$$y_c = 1 - y_d \tag{5.71}$$

$$x_c = 1 - x_d = SOC \tag{5.72}$$

Here subscripts c and d stands for charging and discharging respectively.

### 5.7.5. Open cell voltage

The value of open cell voltage is different for charging and discharge process. It also depends on the state of discharge (x) of the battery. From the Valence data sheet the maximum charge voltage at zero discharge state (x=0) is 14.6 V and maximum value of discharge voltage with same condition is 13.45 V.

### 5.7.6. Internal resistance

The internal resistance is defined by following equation with only the maximum value at discharge take from the data sheet.

The value of internal resistance is also dependent on the charging and discharge state. With constant current discharge, the value of voltage decreases. A linear relation arises between voltage and resistance by above equation.

### 5.7.7. Verification of battery model

The battery modelled is Lithium ion battery based on the Valence data sheet. The modelled was previously verified in the thesis work of F. Jacobs [11] with result for discharge curve as shown in figure 5.27 . The battery model is compared with Valence data sheet in terms of voltage with increasing state of discharge.

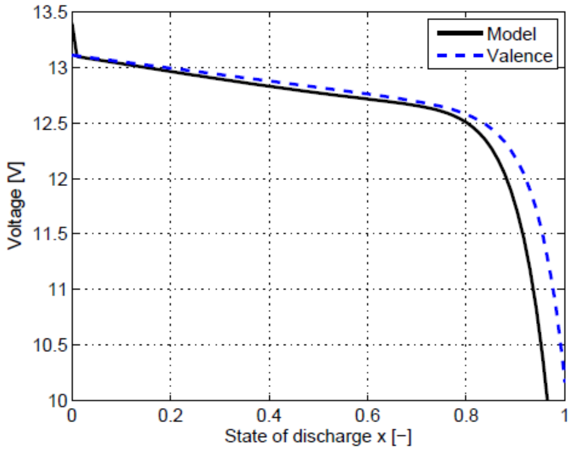



Figure 5.27: Difference in discharge curve by Valence and calculated by the model [11]

## 5.8. Power management system (PMS)

The PMS system was modelled on constant power requirement from the generators to keep the DC voltage at constant value. The load is assumed to be varying as an sinusoidal curve hence the excess and reduced power requirement will be fulfilled by the energy storage which in this thesis is battery. The power management system also takes into account the SOC of battery making it useful for load levelling with value between 0.2-0.8. When the SOC decreases below 0.2 the battery stops supplying the excess power needed for high peak requirements and in turn charges itself when the power requirement goes down. Similarly when SOC value increases above 0.8 the battery stops charging itself thereby disconnecting itself from the grid and supplying power during the high or peak power requirements. Following figure gives an overview of PMS system.

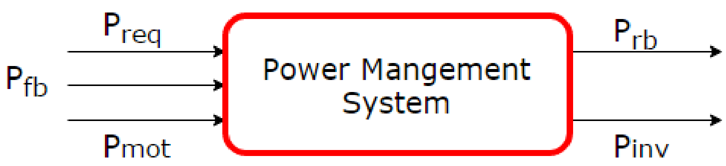



Figure 5.28: PMS overview

Where,
$P_{req}$ = Reference power, $P_{fb}$ = Power from battery, $P_{mot}$ = Power required by motor and load $P_{inv}$ = Power Required from DC bus, $P_{rb}$ = Power to battery

# 6
# Simulation and Results

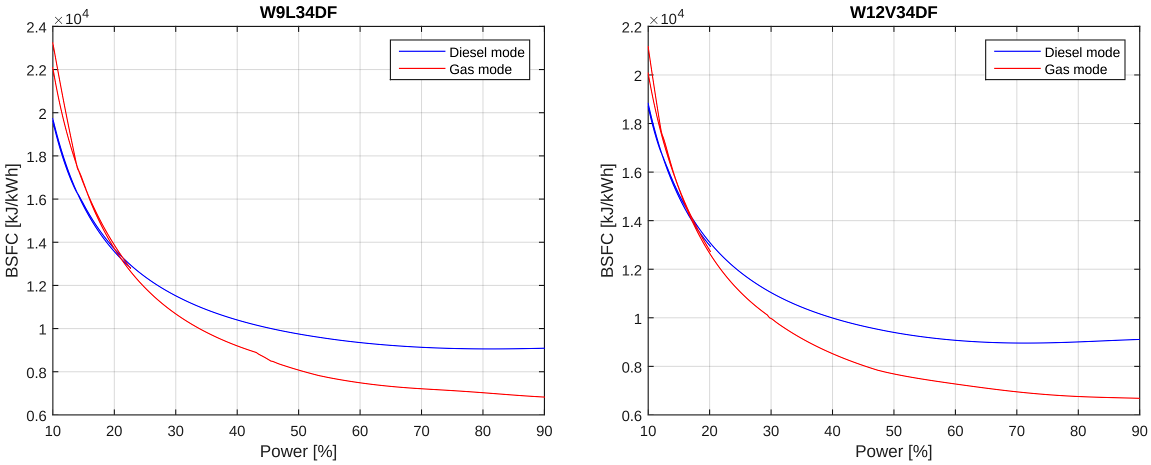
## 6.1. Dual Fuel Engine

In this section simulation were carried for engine as an independent component to measure specific fuel consumption and emission with varying engine load for two modes of operation: Diesel mode, Gas mode. Fuel consumption and emission are compared for following two engine:

- W9L34DF
- W12V34DF

### Specific Fuel Consumption

Figure 6.1 shows specific fuel consumption for two engines types. The specific fuel consumption (SFC) is measured for varying load from 10% to 90% maximum continuous rating (MCR) of the engine. It is measured for two different modes of operation as discussed above. When the engines is under gas mode gaseous fuel is the main fuel main fuel and under the diesel mode operation diesel is the main fuel.




(a) BSFC of W9L34DF

(b) BSFC of W12V34DF

Figure 6.1: Break specific fuel consumption

As it can be seen from the results under gas mode the engine does not perform well under low load condition and also under transient load condition. Further as the load increases SFC of engines under gas mode is lower compared to diesel mode operation. This makes DF engine feasible to make them run at comparatively higher loads and less transient loading condition for gas mode operation.

### Emission

Figure 6.2 and 6.3 shows $CO_2.SO_x$ and particulate matter (PM) emissions for the two engine for various load under diesel and gas mode operation.

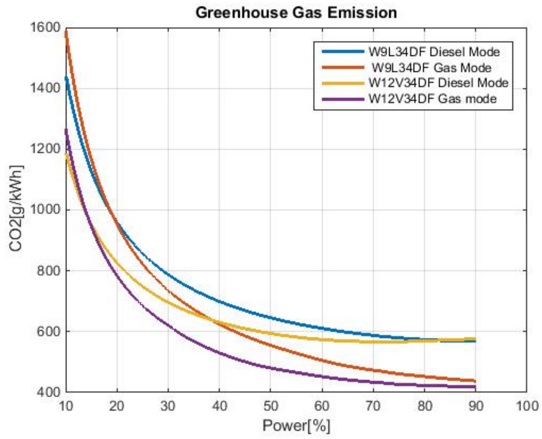
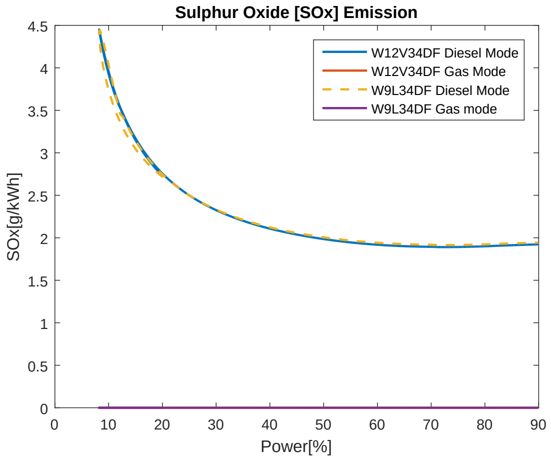
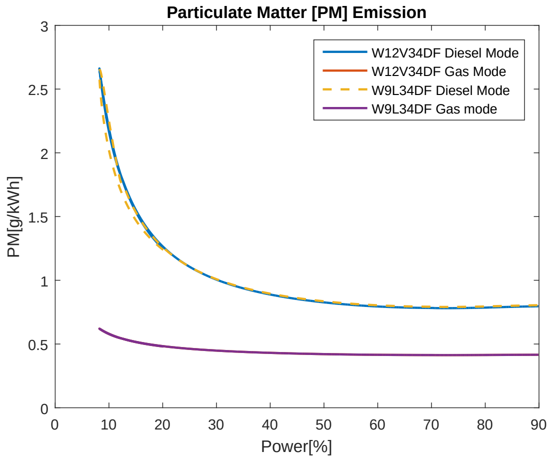



Figure 6.2: $CO_2 Emission$




(a) $SO_x$ emission




(b) PM Emission

Figure 6.3: $SO_x$ and $PM$ emission

As it can be seen in figure 6.2 the green house gas is almost directly proportional to the specific fuel consumption of the engine which in turn is dependent on the engine load. Further for a DF engine running under diesel mode the $SO_x$ emission is almost inversely proportional to the engine load. Since there is approximately no sulphur content in the gas fuel and the pilot fuel during the gas mode operation of the DF engine the $SO_x$ emission during gas mode operation is approximately zero.

As seen from the figure 6.3b the particulate emission of a DF engine running under diesel and gas mode with difference in range of few grams/kWh.

## 6.2. Operation profile

The platform supply vessel can have different modes of operation. However this study is limited to distinct operating modes up to 4 which includes transit, DP high(loading/offloading), DP low(loading/offloading) and standby. Due to unavailability of the real data for this vessel and often the companies classify sensitive information regarding the operation profile this section data will be taken from the past work. The proposed operation for this vessel is given in table:

Table 6.1: Vessel operation description

| Operation Distance [nm] | |
|---|---|
| Sore Base – Installation A [nm] | 200 |
| Sore Base – Installation B [nm] | 180 |
| Sore Base – Installation C [nm] | 250 |
| Sore Base – Installation D [nm] | 220 |
| A – B [nm] | 20 |
| A – C [nm] | 60 |
| A – D [nm] | 50 |
| B – C [nm] | 20 |
| B – D [nm] | 10 |
| C – D [nm] | 30 |

Table 6.2: Operation profile

| Operation | Duration [hr] | Average Power Demand [%] | Variation [+/- % | Max Power Demand [%] | Min Power Demand [%] |
|---|---|---|---|---|---|
| **Harbour** | 6 | 2 | 0 | 2 | 2 |
| **Transit** | 17 | 40 | 10 | 45 | 35 |
| **DP High** | 3 | 45 | 30 | 60 | 30 |
| **Transit** | 1 | 70 | 10 | 100 | 80 |
| **DP high** | 2 | 45 | 30 | 60 | 30 |
| **DP Low** | 8 | 20 | 50 | 30 | 10 |
| **Transit** | 1 | 70 | 10 | 100 | 80 |
| **DP High** | 2 | 45 | 30 | 60 | 30 |
| **DP Low** | 8 | 20 | 50 | 30 | 10 |
| **Transit** | 2 | 70 | 10 | 100 | 80 |
| **DP High** | 3 | 45 | 30 | 60 | 30 |
| **DP Low** | 15 | 20 | 50 | 30 | 10 |
| **Transit** | 18 | 40 | 10 | 45 | 35 |

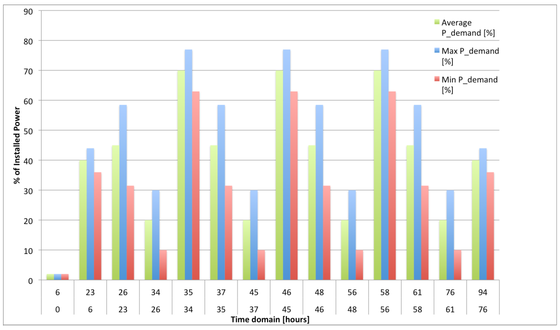



Figure 6.4: Load Profile[50]

For the maximum time in the operation profile the power demand is below 50% of the MCR. During the DP mode operation it is required to operate more number of engines than required for redundancy. For the simulation the above operation profile is given as load to the propulsion system through the electric motors running at 750 rotations per minute (rpm) as discussed earlier. The above operation profile is converted into seconds with power requirement in table 6.5.

The load profile is used to compare different power plant configurations based on particular criteria. From the operation profile of a vessel a load profile is designed that will be directly be given to the motor in the configuration through the rotational dynamics. For the simulation axillary power is assumed to be included in the total load given to the electric motor.

For current work it is assumed the vessel is operating in North sea. The power profile under DP is dependent on the types of waves experienced by the vessel. There are also other loads like the wind which will not be considered for current analysis. The power requirement changes, with the wave period as the wave passes along the vessel. This wave period is used to give the desired variation with a sinusoidal wave curve with some average power demand during the DP mode.

## 6.3. Theoretical case study

For current study a Maersk anchor handling vessel Stingray is considered. It is a platform support vessel with propulsion plant layouts discussed later in this chapter. Because of not enough information available regarding this vessel, the propulsion plant is considered to have following engines types:
W6L34DF : 3000 kW
W8L34DF : 4000 kW
W12V34DF : 5760 kW
The focus is made for transient loading condition which exists generally during the DP operation. Hence the

Table 6.3: Vessel description

| **Vessel : Stingray** | |
|---|---|
| DP Class | 3/DYNPROS-AUTRO |
| Area of Operation | North sea |
| Speed Eco. [kn] | 12.5 |
| Speed Max [kn] 15 | 14 |
| Power [kW] | 24000 |

simulations are carried only when the vessel is performing DP operation. Here the average load and variation from the average load is taken from the operation profile described in table 6.2. For the simulation purpose a basic assumption is made, where load is assumed to be having sinusoidal nature with bias nature over the average load. The load is taken from the operation profile with amplitudes of sine wave equal to the variation from the average load. The wave length of the sine wave is assumed from the data [51] which is equal to 4.5s for the DP high operation and 5.5s for DP low operation. Figure 6.5 shows the DP high and low loads for 100 seconds for which the simulation will be carried.
Following configurations were taken into consideration:

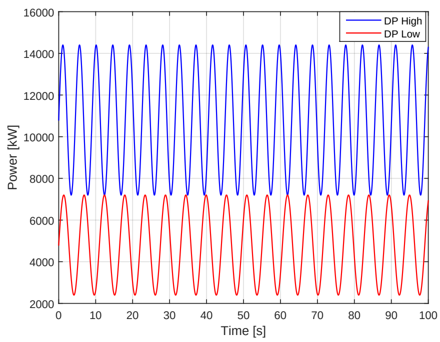



Figure 6.5: Load profile

- **Configuration 1:** Six W8L34DF engine installed two engine rooms
- **Configuration 2:** Eight W6L34DF engine installed two engine rooms
- **Configuration 3:** Four W6L34DF engine and two W12V34DF engine installed in two engine rooms

In the above configurations energy storage is referred to battery pack.

The simulations were carried for the above mentioned configurations with following cases:

- **Case 1:** Without energy storage for DP high and low operation. In this case of propulsion plant, batteries are not used for the DP operation and hence the engines have to take the dynamic loads and respond accordingly. Since the engines have to perform under dynamic loads this causing engine to knock and misfire while performing under the DP operation.

- **Case 2:** With energy storage for load levelling under DP high and low operation. In this case of propulsion plant, batteries are integrated to be used along with engines for the DP operation. Here the batteries are used for load levelling, hence the engines are running at some average load. This load levelling role of battery prevents the engine to cross the knock and misfire limits during the dynamic loads for the DP operation. This case is more efficient compared to case 1 in terms of fuel consumption with reduced emissions and improved knock and misfire rating. Hence the overall life of engine increases and the maintenance cost of the complete plant is considerable reduced. Since there is reduced knock, vibrations are also reduced considerably. The size of battery for this case is based on the operation profile and maximum amplitude of the load to be levelled.

- **Case 3:** In this case energy storage being used as Uninterrupted power source (UPS) for DP high and low operation. Under this case of propulsion system, one of the engines in each of the two engines rooms is switched off, hence number of prime movers running on part loads are less which in turn increases the overall load on the remaining running engines. The engine to be switched off depends on the operation profile and the average load at which the engines will be running. The class rules requires the battery used as UPS should be able to provide power for 30 minutes, when there is any compartment failure or single fault condition. Hence the size of energy storage capacity is equal to the energy produced by the engine that will be switched off during the DP operation for 30 minutes.

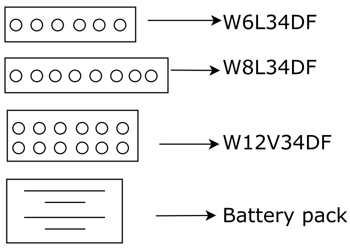



Figure 6.6: Symbol description

### 6.3.1. Configuration 1

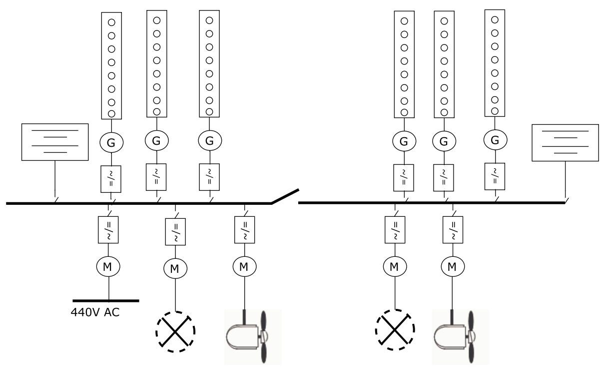



Figure 6.7: Propulsion plant layout with six W8L34Df engines and battery packs

This configuration of propulsion system is a standard propulsion plant layout with six W8L34DF engines installed in two separate engine rooms. Because of the redundancy requirement during the DP operation all six engines are running at part loads. For the case 2 and 3 layout the engines are integrated with the battery pack. Simulations were carried for all the three above mentioned cases with results presented below.

### Case 1

For this case the engines have to perform under dynamic loads which causes engines to knock under the DP high operation. Under the DP low operation engine experiences both knock and misfire condition. This case is inefficient in terms of fuel consumption and emission. Because of the high knock and misfire condition the overall lifetime of engines is considerably reduced with increased vibrations on-board the ship. The maintenance cost is also high for this case of propulsion plant.

Table 6.4: Summary of fuel consumption, cost and emission for Case 1 of configuration 1 for DP operation

| | |
|---|---|
| Total Fuel Consumption[MJ/trip] | 3196362.112 |
| Fuel Cost [USD] | 13846.59 |
| Engine Installation Cost [USD] | 8400000 |
| Battery Pack Installation Cost [USD] | 0 |
| Total Installation Cost [USD] | 8.4 million |
| $CO_2$ Emission [ton/trip] | 179.0787 |
| $SO_x$ Emission [ton/trip] | 0 |
| PM Emission [kg/trip] | 5.500352 |

### Case 2

For this case of current configuration all the six W8L34DF engines will be running alongside the integrated battery pack used for the load levelling of the dynamic loads occurring during the DP operation. For the current study the size of battery pack is assumed to be 2000 kWh. Because of the class requirements there are two battery packs installed on-board in two separate engine rooms with capacity of 1000kWh each.

Table 6.5: Summary of fuel consumption, cost and emission for Case 2 of configuration 1 for DP operation

| | |
|---|---|
| Total Fuel Consumption[MJ/trip] | 3169573.763 |
| Fuel Cost [USD] | 13730.59 |
| Engine Installation Cost [USD] | 8400000 |
| Battery Pack Installation Cost [USD] | 1100000 |
| Total Installation Cost [USD] | 9.5 million |
| $CO_2$ Emission [ton/trip] | 177.5779 |
| $SO_x$ Emission [ton/trip] | 0 |
| PM Emission [kg/trip] | 5.318 |

### Case 3

For this layout the engine to be switched off will be one of the W8L34DF engine leaving two W8L34DF engines running per engine room. Hence for the DP operation there will be four engines running and battery pack. The total dynamic load will be taken by the remaining four running engines and the battery pack. Here the main role of energy storage is both as load levelling and peak shaving. It performs as peak shaving storage if the load requirement from the prime mover exceeds their maximum capacity. Apart from this it performs load levelling operation making the W8L34DF engines running at some average load. The total capacity of energy storage to be installed is equal to power produced by two W8L34DF engines that are switched off for 30 minutes, that is 4000 kWh. This 4000 kWh capacity will be installed as two 2000 kWh battery pack in each of the separate battery rooms.

Table 6.6: Summary of fuel consumption, cost and emission for Case 3 of configuration 1 for DP operation

| | |
|---|---|
| Total Fuel Consumption[MJ/trip] | 2586995.763 |
| Fuel Cost [USD] | 11206.87 |
| Engine Installation Cost [USD] | 8400000 |
| Battery Pack Installation Cost [USD] | 2200000 |
| Total Installation Cost [USD] | 10.6 million |
| $CO_2$ Emission [ton/trip] | 144.9385 |
| $SO_x$ Emission [ton/trip] | 0 |
| PM Emission [kg/trip] | 6.177 |

### 6.3.2. Configuration 2

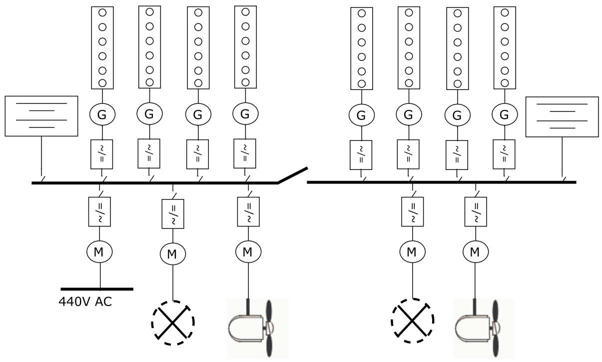



Figure 6.8: Propulsion plant layout with six W6L34DF engines and battery packs

This configuration is installed with eight W6L34DF engines with four engines in two separate engine rooms. Because of the redundancy requirement during the DP operation all eight engines are running at part loads. For the case 2 and 3 layout the engines are integrated with the battery pack. Simulations were carried for all the three above mentioned cases with results presented below.

#### Case 1

For this case the engines have to perform under dynamic loads which causes engines to knock under the DP high operation. Under the DP low operation engine experiences both knock and misfire condition. This case is inefficient in terms of fuel consumption and emission. Because of the high knock and misfire condition the overall lifetime of engines is considerably reduced with increased vibrations on-board the ship. The maintenance cost is also high for this case of propulsion plant.

Table 6.7: Summary of fuel consumption, cost and emission for Case 1 of configuration 2 for DP operation

| | |
|---|---|
| Total Fuel Consumption[MJ/trip] | 3199193.429 |
| Fuel Cost [USD] | 13858.91 |
| Engine Installation Cost [USD] | 8400000 |
| Battery Pack Installation Cost [USD] | 0 |
| Total Installation Cost [USD] | 8.4 million |
| $CO_2$ Emission [ton/trip] | 179.2374 |
| $SO_x$ Emission [ton/trip] | 0 |
| PM Emission [kg/trip] | 9.752 |

#### Case 2

For this case of current configuration all the eight W6L34DF engines will be running alongside the integrated battery pack used for the load levelling of the dynamic loads occurring during the DP operation. For the current study it is assumed that the size of battery pack is 2000 kWh. Because of the class requirements there are two battery packs installed on-board in two separate engine rooms with capacity of 1000kWh each.

Table 6.8: Summary of fuel consumption, cost and emission for Case 2 of configuration 2 for DP operation

| | |
|---|---|
| Total Fuel Consumption[MJ/trip] | 3169114.778 |
| Fuel Cost [USD] | 13728.61 |
| Engine Installation Cost [USD] | 8400000 |
| Battery Pack Installation Cost [USD] | 1100000 |
| Total Installation Cost [USD] | 9.5 million |
| $CO_2$ Emission [ton/trip] | 177.5522 |
| $SO_x$ Emission [ton/trip] | 0 |
| PM Emission [kg/trip] | 9.461 |

#### Case 3

For this layout the engine to be switched off will be one of the W6L34DF engine, leaving three W6L34DF engines running per engine room. Hence for the DP operation there will be six engines running and battery pack. The total dynamic load will be taken by the remaining six running engines and the battery pack. Here the main role of energy storage is both as load levelling and peak shaving. It performs as peak shaving storage if the load requirement from the prime mover exceeds their maximum capacity. Apart from this it performs load levelling operation making the W6L34DF engines to run at some average load. The total capacity of energy storage to be installed is equal to power produced by two W6L34DF engines that are switched off for 30 minutes, that is 3000 kWh. This 3000 kWh capacity will be installed as two 1500 kWh battery pack in each of the separate battery rooms because of the class requirement.

Table 6.9: Summary of fuel consumption, cost and emission for Case 3 of configuration 2 for DP operation

| | |
|---|---|
| Total Fuel Consumption[MJ/trip] | 2733806.953 |
| Fuel Cost [USD] | 11842.85 |
| Engine Installation Cost [USD] | 8400000 |
| Battery Pack Installation Cost [USD] | 1650000 |
| Total Installation Cost [USD] | 10.05 million |
| $CO_2$ Emission [ton/trip] | 153.1637 |
| $SO_x$ Emission [ton/trip] | 0 |
| PM Emission [kg/trip] | 7.106 |

### 6.3.3. Configuration 3

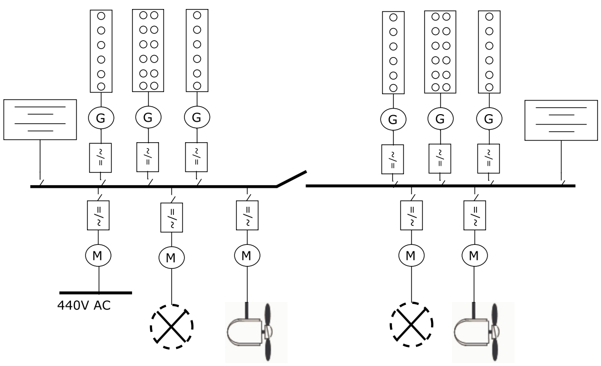



Figure 6.9: Propulsion plant layout with four W6L34Df and two W12V34DF engines with battery packs

This configuration is installed with four W6L34DF engines and two W12V34DF engines in two separate engine rooms. Because of the redundancy requirement during the DP operation all the eight engines are running at part loads. For the case 2 and case 3 layout the engines are integrated with the battery pack. Simulations were carried for all the three above mentioned cases with results presented below.

### Case 1

For this case the engines have to perform under dynamic loads which causes engines to knock under the DP high operation. For this operation the W6L34DF engine performs under high knock while W12V34DF engine performs under low knocking condition. Under the DP low operation both the types engines have knock and misfire condition, with W6L34DF experiencing more of such conditions while W12V34DF with low knocking. This case is inefficient in terms of fuel consumption and emission. Because of the high knock and misfire condition the overall lifetime of engines is considerably reduced with increased vibrations on-board the ship. Maintenance cost is also high for this case of propulsion plant.

Table 6.10: Summary of fuel consumption, cost and emission for Case 1 of configuration 3 for DP operation

| | |
|---|---|
| Total Fuel Consumption[MJ/trip] | 2165045.146 |
| Fuel Cost [USD] | 9378.976 |
| Engine Installation Cost [USD] | 8400000 |
| Battery Pack Installation Cost [USD] | 0 |
| Total Installation Cost [USD] | 8.4 million |
| $CO_2$ Emission [ton/trip] | 121.2984 |
| $SO_x$ Emission [ton/trip] | 0 |
| PM Emission [kg/trip] | 10.987 |

### Case 2

For this case of current configuration all the four W6L34DF and two W1234DF engines will be running alongside the integrated battery pack used for the load levelling of the dynamic loads occurring during the DP operation. For the current study it is assumed that the size of energy storage is 2000 kWh. Because of the class requirements there are two battery packs installed on-board in two separate battery rooms with capacity of 1000kWh each.

Table 6.11: Summary of fuel consumption, cost and emission for Case 2 of configuration 3 for DP operation

| | |
|---|---|
| Total Fuel Consumption[MJ/trip] | 2165525.964 |
| Fuel Cost [USD] | 9381.058 |
| Engine Installation Cost [USD] | 8400000 |
| Battery Pack Installation Cost [USD] | 1100000 |
| Total Installation Cost [USD] | 9.5 million |
| $CO_2$ Emission [ton/trip] | 121.3253 |
| $SO_x$ Emission [ton/trip] | 0 |
| PM Emission [kg/trip] | 10.648 |

### Case 3

For this layout the engine to be switched off will be W12V34DF engine, leaving two W6L34DF engines running per engine room. Hence for the DP operation there will be four W6L34DF engines running and battery pack. The total dynamic load will be taken by the remaining four running engines and the battery pack. Here the main role of energy storage is both as load levelling and peak shaving. It performs as peak shaving storage if the load requirement from the prime mover exceeds their maximum capacity. Apart from this, it performs load levelling operation making the W6L34DF engines running at some average load. For the DP high operation the W6L34DF engine performs well within the knock and misfire limits. Under the DP low operation W6L34DF engine crosses the knock limit causing mild knocking condition during these operation. The total capacity of energy storage to be installed is equal to power produced by two W12V34DF engines that are switched off for 30 minutes, that is 6000 kWh. This 6000 kWh capacity will be installed as two 3000 kWh battery pack in each of the separate battery rooms because of the class requirements.

Table 6.12: Summary of fuel consumption, cost and emission for Case 3 of configuration 3 for DP operation

| | |
|---|---|
| Total Fuel Consumption[MJ/trip] | 1508103.141 |
| Fuel Cost [USD] | 6533.103 |
| Engine Installation Cost [USD] | 8400000 |
| Battery Pack Installation Cost [USD] | 3300000 |
| Total Installation Cost [USD] | 11.7 million |
| $CO_2$ Emission [ton/trip] | 84.49269 |
| $SO_x$ Emission [ton/trip] | 0 |
| PM Emission [ton/trip] | 2.175 |

## 6.4. Sensitivity analysis

From the simulations carried for different configurations with different cases it is indeed clear for using any configurations of gaseous fuel power plant without the energy storage for dynamic loads. Though the installation cost is low for case 1 of all the configurations it is not a feasible choice for a propulsion plant for a gaseous fuelled ships as the engines are literally operating under knock and misfire condition all the time for dynamic loads. Through integration of batteries with the gas engines as shown in case 2 and case 3 the engines are operating in knock and misfire free zone will low fuel consumption and emissions. The total installation cost of these two cases is high but with saving in fuel, emission, maintenance the return on investment might in few years if the load variation is high or if the number of trips the vessel is performing is high. The good choice in terms of fuel saving might be configuration 3 though under the DP low operation there is case of slight knock as only two W6L34DF engines are running under low load and experiencing a substantial load variation even after integration of batteries. Since for the current operation profile DP low operation occupies a substantial portion of the total profile it is not the prime choice. The most viable choice will be to use configuration 1 with case 2 if the number of trips is low and to use case 3 if the number of trips that the ship goes is high.

# 7 Discussion, Conclusion and Recommendation

## 7.1. Discussion

This work presented a way to integrate natural gas fuelled engine with energy storage for DP3 class vessels with complex operational profiles. This integration of energy storage with standard propulsion plant gives hybrid propulsion plant, where it was identified if this hybrid propulsion plant of dual fuel engine with energy storage is advantageous over standard propulsion plant based on few defined parameters.

The operation profile will show various power demands starting from port operation to long distance transit operation. This modes of actions are considered not complex part of the operation profile. The profound study of operation profile shows that the operation mode with respective power demand have to be analysed. This brings the dynamic loads and dynamic power demands to be evaluated, as these loads represent the biggest challenge while designing the power plant of the ship. Hence for the current study, focus was made only for the DP operation load profile. Knowing the power demand for the DP operation and average resistance the engines can be optimized to operate efficiently at part loads for maximum time during the DP operation. The dynamic loads creates peaks over the average load at which the engine is running. For handling this dynamic loads electric propulsion has proven ability over the standard direct drive propulsion systems. The engines should be capable of handling this dynamic loads by ramping up or down in sufficient amount of time. During this ramping action performed by engines, it should not loose its speed which might otherwise affect the frequency of the electrical power produced by the generator. It also has prevent the knocking and misfire condition which may permanently damage its performance on a longer run. To prevent this condition, it is important that engines are made to run at some average load with less variation over the average load.

Also the study showed that the performance of dual fuel engine under the gas mode is reasonably poor compared to standard diesel mode. Hence this implicates for the integration of energy storage option with response time almost instantaneous to handle the sudden peaks and troughs over the average load demand. The selection of energy storage is important for optimal power management for their longer period of operation. Also it is important to select the type of role to be performed by the energy storage and how it will be connected to the propulsion plant. This connection can be as an spinning reserve where it will provide excess speed required by the generator to produce the required power. Another case will be as a non spinning reserve where the energy storage is directly connected to the grid and provides the electrical power to the grid directly via the power management system.

Another focus is on the emission of the hybrid power plant with main focus on green house gases, $SO_x$ and PM. The study also showed that the natural gas fuelled propulsion plant is most economical when using it in emission controlled areas with stricter laws on emissions making it hard to use heavy or intermediate fuel oil for such areas. It was clear that for the gas mode of DF engine had with lower greenhouse gas and PM emission and approximately no $SO_x$ emission. Along with all this the engine manufacturers are also trying to optimize the engine efficiency at different engine loads regardless of their optimal operation point with lower emission values to meet the new Tier rules.

The first steps to meet all the above rules of emission and get maximum economical benefits will be to have an in depth evaluation of operation profile with the degree of dynamics appearing on the loads and its amplitude that the vessel will experience. After this it becomes clear if the hybridization of the natural gas fuelled vessel is feasible or not. With advancing technological development in batteries being used as energy storage and its ability to be used for varying loads, this integration for hybrid propulsion system will be economical and environmentally friendly.

## 7.2. Conclusion

The results show that for the given operation profile, DP operation with dynamic loading condition has significant effect on the engine performance. The effect is in terms of high engine knock and misfire condition. These conditions depend upon the degree of load variation and the time of transition of this varying load. High load steps will result in heavy knocking in the engine. Lower value of time transition that, which is frequently changing load will result in high misfire condition. This makes the DP high operation to perform under both knock and misfire with heavy vibration while DP low operation to perform only under misfire condition with low vibration. This also depends upon the degree of load dynamics and its value over the average load. For any propulsion plant layout running on gas fuel and experiencing DP loads, integration of energy storage with standard propulsion plant is an appropriate choice in terms of less fuel consumption, reduced emission and vibration. Even though hybridization of power plant is costly compared to standard propulsion plant, the fuel saving, lower maintenance cost, and reduced emissions will make it profitable within few years of operation.

Models were developed for dual fuel engine, generator, motor and battery. A DC grid model is further developed with converter and inverter for the integration of above-mentioned models. Parametric analysis is done for the different configurations developed by the author. This parametric analysis includes comparison based on the fuel consumption, total installation cost, running cost and emission.

Based on cost factor, integration of energy storage in the standard propulsion plant will provoke a higher cost. It needs to be decided whether to use the engine under knock & misfire condition or increase the initial installation cost which will suffice that the engine shall operate in a safe zone. Taking installation cost into consideration the battery is best used under load levelling operation.

With the stringent emission laws, integration of energy storage will make it a favourable choice. For the energy storage being used as UPS the emission values are least, based on the fact that one of the engine in the engine room is switched off. This value will depend on the overall load profile of the vessel.

While selecting the type of propulsion plant for a DP3 class offshore supply vessel where space is a major concern, proper selection of the number of engines has to be done. Depending upon the power requirement the size of engine can be varied. The total numbers of engines to be taken into consideration while installation has to be six in two separate engine rooms. Such configurations are optimum in terms of fuel consumption, emission and cost.

Conclusion is that gas fuelled engine cannot perform under the dynamic loads without experiencing knock and misfire. Hence it is prudent choice to integrate energy storage with the gas engines which can take the sudden load peaks. More the variation exists in the operation profile, more it favours for hybridization solution. The saving in terms of fuel consumption and emission are relatively low but technological improvements in battery for energy storage will make it more economical and environmental friendly in near future.

## 7.3. Recommendation

The current study was carried out using only available theoretical data. There was not much real time data in terms of operation profile, standard machinery configuration using natural gas dual fuel engines. Implementation of such hybrid technology for a gas fuelled offshore supply vessel will be a huge step forward. The work can further be advanced for integrating flywheels, super capacitors and fuel cells with hybrid propulsion plant. The extensive research on large scale, high capacity lithium batteries is required. This research should also be intensified to study the battery dynamics in terms capacity. This work can further be expanded to the overall operation profile of an offshore supply vessel to get more prudent results which can be compared with current propulsion plant being used. This study should also be expanded to different types of DP3 vessels like pipe laying vessels, floating production storage and offloading (FPSO), dredgers and many more which have high auxiliary load requirement that has to be taken into consideration during design phase of the propulsion plant.

# A Parameters and specifications

## A.1. Dual fuel engine

Table A.1: Dual fuel engine parameters

| | W6L34DF | W8L34DF | W9L34DF | W12V34DF |
|---|---|---|---|---|
| Stroke [-] | 4 | 4 | 4 | 4 |
| Nominal speed [rpm] | 750 | 750 | 750 | 750 |
| Power [kW] | 3000 | 4000 | 4500 | 6000 |
| Bore [m] | 0.34 | 0.34 | 0.34 | 0.34 |
| Stroke [m] | 0.4 | 0.4 | 0.4 | 0.4 |
| Number of cylinder [-] | 6 | 8 | 9 | 12 |

## A.2. Fuel properties

Table A.2: Diesel fuel specification

| DMB | |
|---|---|
| C content | 0.865 (mass fraction) |
| S content | 0.005 (mass fraction) |
| H content | 0.13 (mass fraction) |
| C/H Ratio | 6.65 |
| Lower Heat Value | 43.315 [$\frac{MJ}{kg}$] |

Table A.3: Pilot fuel specification

| DMX | |
|---|---|
| C content | 0.865 (mass fraction) |
| S content | 0 (mass fraction) |
| H content | 0.135 (mass fraction) |
| C/H Ratio | 6.4 |
| Lower Heat Value | 44.612 [$\frac{MJ}{kg}$] |

Table A.4: Gas fuel specification

| LNG - MN70 | |
|---|---|
| Methane number | 70 |
| Heating Value | 49.620 [$\frac{MJ}{kg}$] |

## A.3. Battery specification

**Manufacturer Valence**
**Type U27-12XP**

Table A.5: Battery specification

| | | |
|---|---|---|
| Nominal Voltage | 12.8 | [V] |
| Nominal capacity (C/5, 23C) | 138 | [Ah] |
| Weight (approx.) | 19.5 | [kg] |
| Specific energy | 91 | $[\frac{Wh}{kg}]$ |
| Discharging current continuous load (25C) | 150 | [A] |
| Discharging current peak load (25C) | 300 | [A] |
| Cut-off voltage (25C) | 10 | [V] |
| Maximum charge voltage | 14.6 | [V] |
| Float voltage (recommended current C/2) | 13.8 | [V] |
| Charge time (C/2) | 2.5 | [h] |
| Maximum internal DC resistance | 5.0 | [m Ω] |

## A.4. Generator

Table A.6: Generator parameter

| **Generator Type** | **Synchronous Machine** | |
|---|---|---|
| Apparent Power | 5000 | kW |
| Voltage | 1000 | V |
| Frequency | 60 | Hz |
| Number of Poles | 10 | - |
| Inertia | 160 | $kgm^2$ |
| Inititial flux values $\psi_{fd}, \psi_{1d}, \psi_{1q}, \psi_{2q}$ | 0.6, 0.525, -0.56, -0.56 | $V \cdot s$ |
| d-axis parameters ( xd, xd', xd'',Tdo', Tdo'') | 2.768, 0.263, 0.209, 1.42, 0.02 | p.u |
| q-axis parameters (xq, xq', xq'', Tqo', Tqo'') | 2.696, 1.2, 0.34, 1.4, 0.14 | p.u |
| Uni-axis parameter (xl, ra) | 0.118, 0.005517 | p.u |

## A.5. Motor

Table A.7: Motor parameter

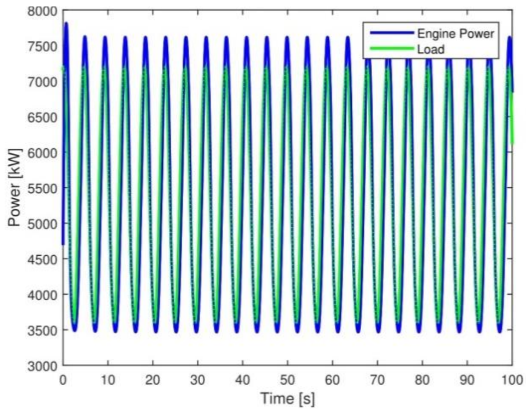
| **Generator Type** | **Asynchronous Machine** | |
|---|---|---|
| Speed | 750 | rpm |
| Voltage | 2200 | V |
| Current | 450 | A |
| Frequency | 40 | Hz |
| Number of Poles | 4 | - |
| Inertia | 160 | $kgm^2$ |
| Inititial flux values $\psi_{ds}, \psi_{qs}, \psi_{dr}, \psi_{qr}$ | 0.00045, -0.37, -0.05, -0.348 | $V \cdot s$ |

# B
# Simulation results

The appendix shows simulation results in terms of power output per engine room of each configurations, specific fuel consumption of a one engine running in this configuration, air-fuel ratio with knock and misfire limits of one engine and engine speed in rotation per minutes (rpm) of one engine running.

## Configuration 1

### Case 1

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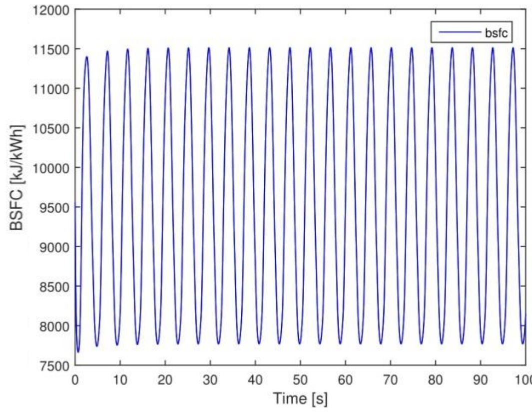


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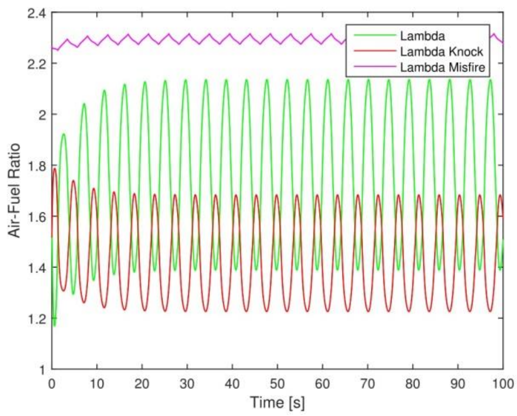


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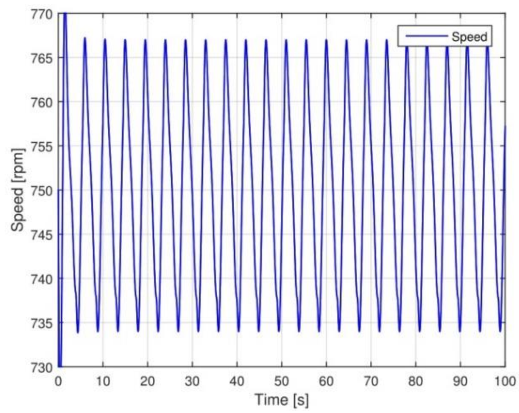
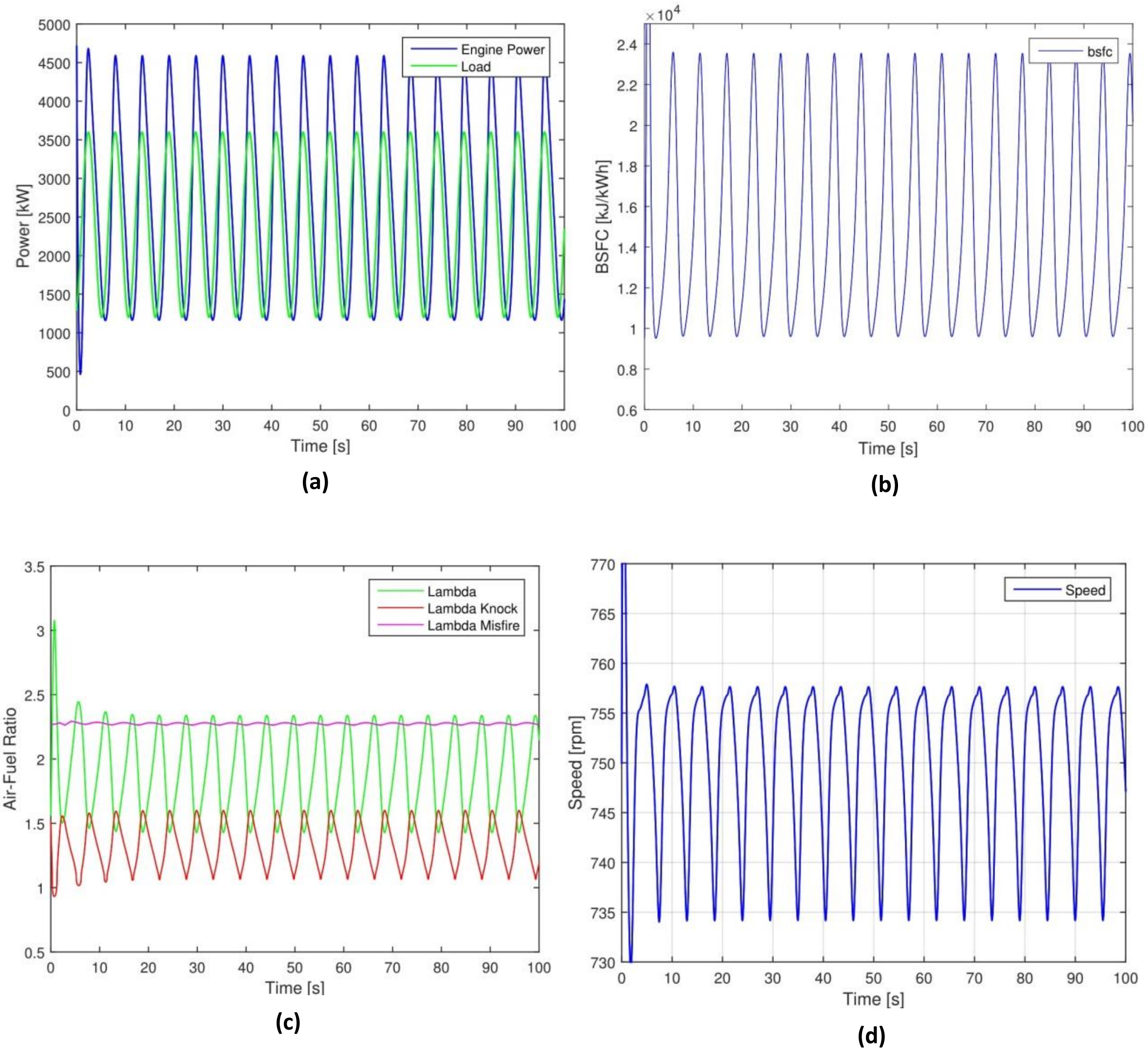


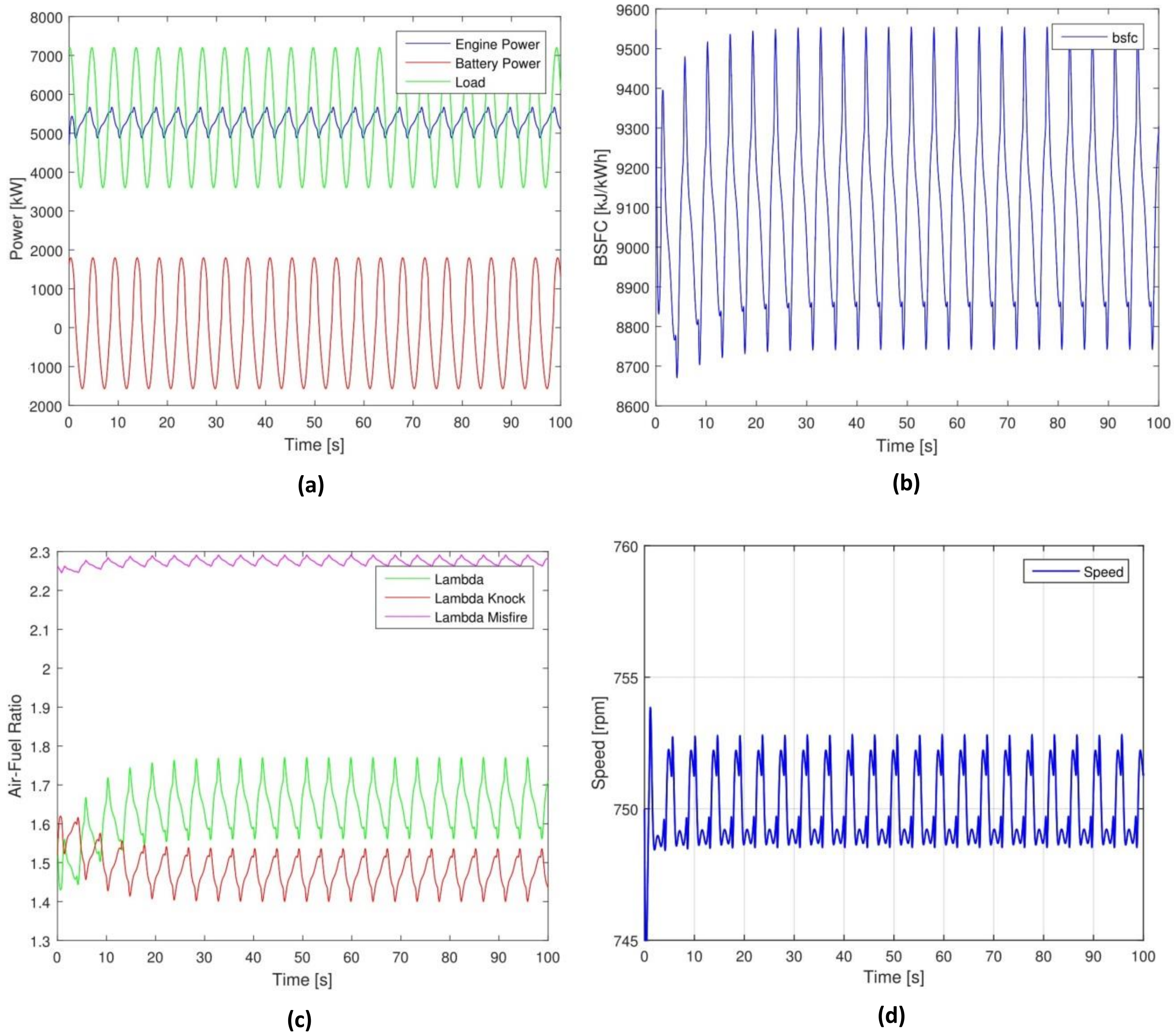

**(d)**

**Propulsion plant performance with per engine room power output (a), specific fuel consumption of one engine(b), air fuel ratio with knock and misfire limits of one engine (c), speed of one engine (d) per engine for the DP high operation**

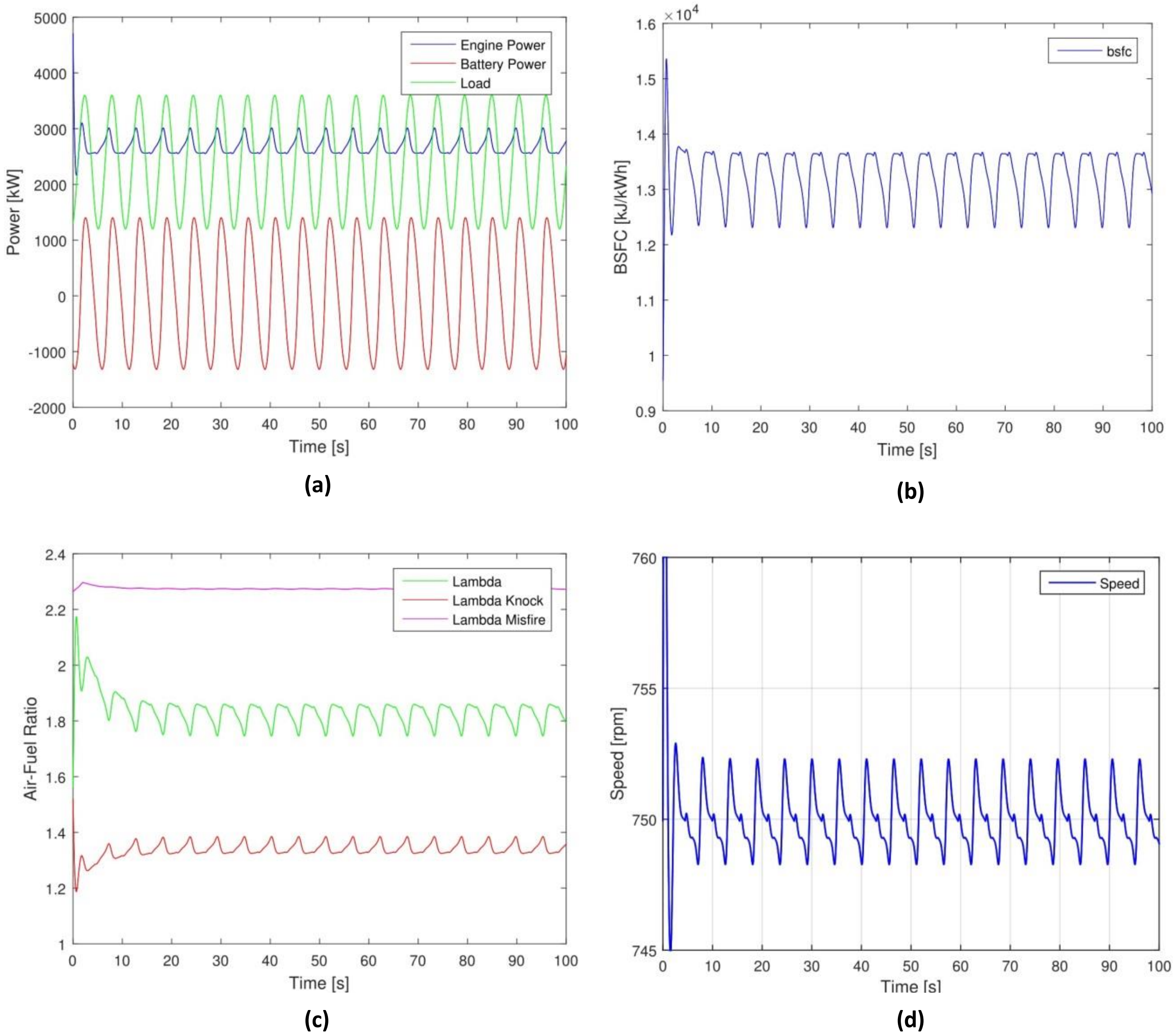



**Propulsion plant performance with per engine room power output (a), specific fuel consumption of one engine(b), air fuel ratio with knock and misfire limits of one engine (c), speed of one engine (d) per engine for the DP low operation**

# Case 2

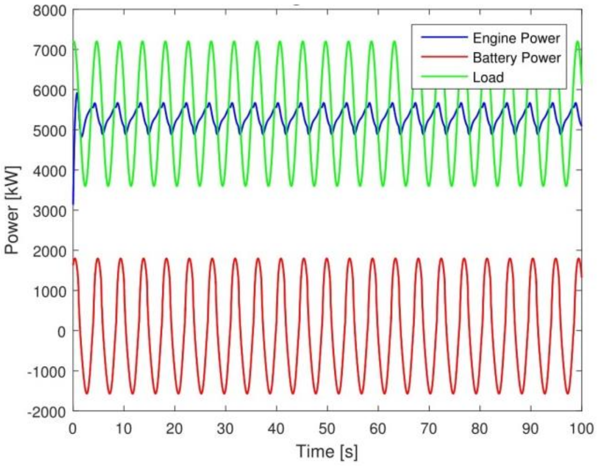



**Propulsion plant performance with per engine room power output (a), specific fuel consumption of one engine(b), air fuel ratio with knock and misfire limits of one engine (c), speed of one engine (d) per engine for the DP high operation**




**Propulsion plant performance with per engine room power output (a), specific fuel consumption of one engine(b), air fuel ratio with knock and misfire limits of one engine (c), speed of one engine (d) per engine for the DP low operation**

# Case 3

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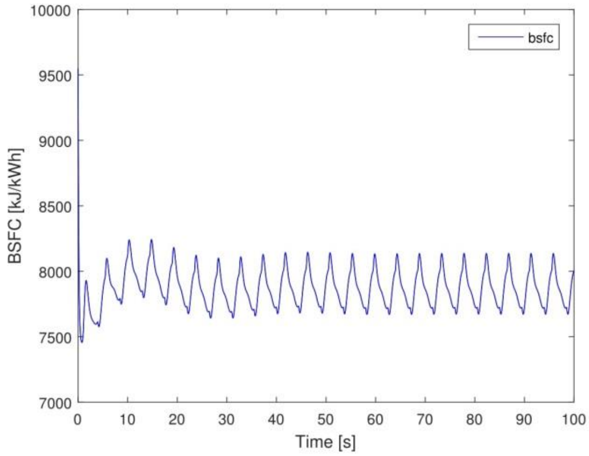


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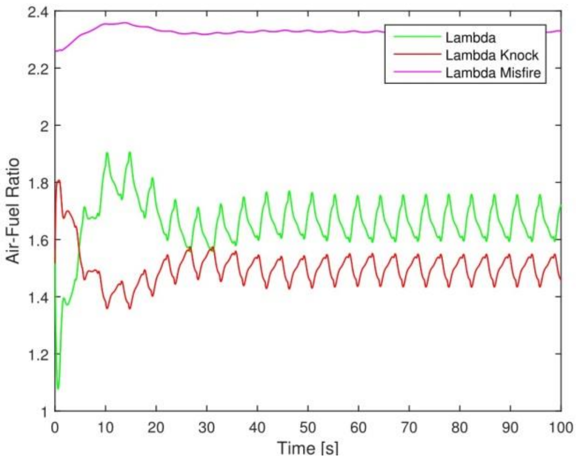


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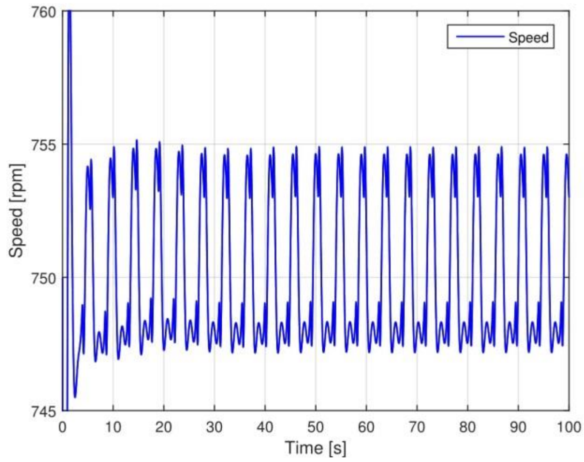
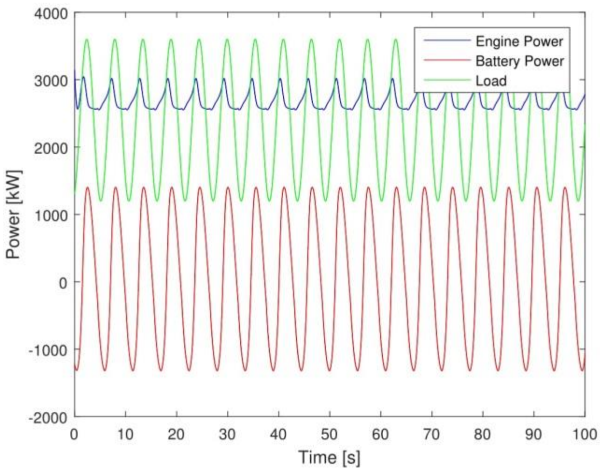



**(d)**

**Propulsion plant performance with per engine room power output (a), specific fuel consumption of one engine(b), air fuel ratio with knock and misfire limits of one engine (c), speed of one engine (d) per engine for the DP high operation**

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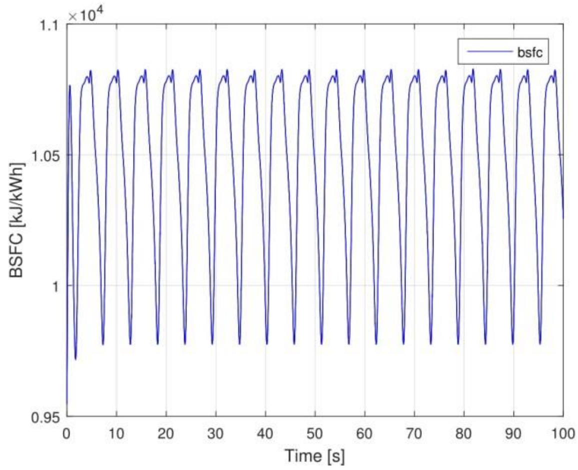


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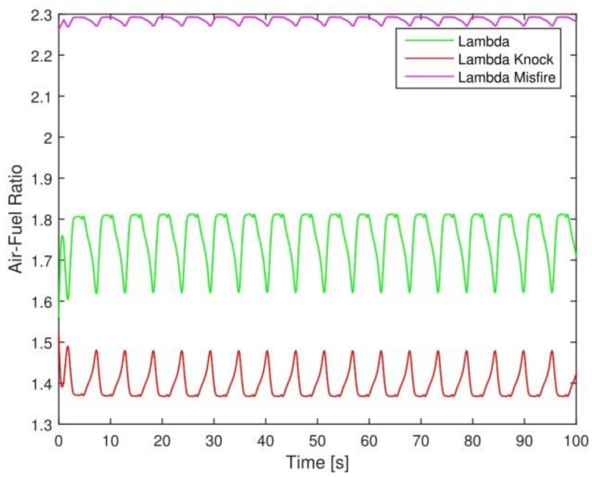


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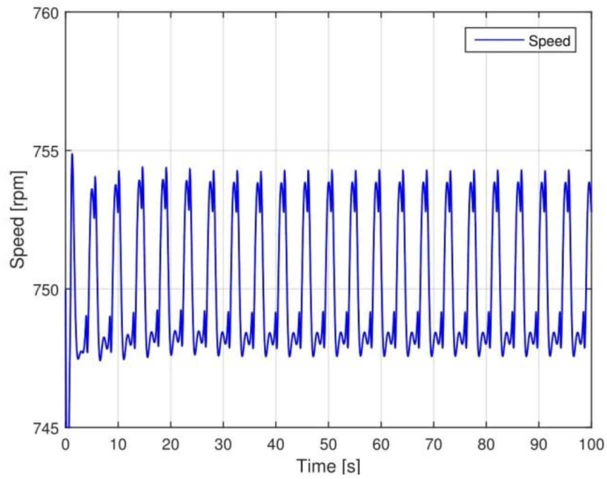
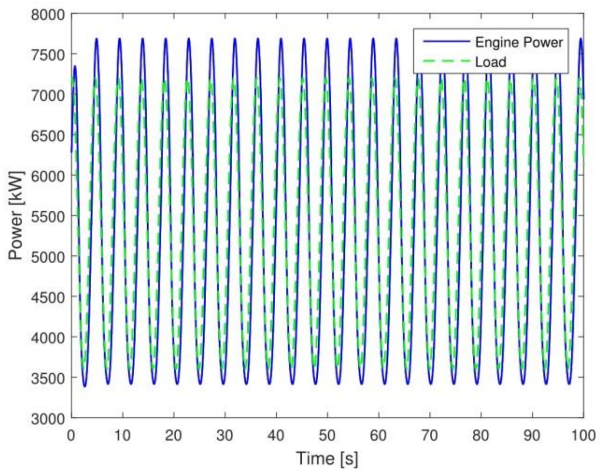



(d)

**Propulsion plant performance with per engine room power output (a), specific fuel consumption of one engine(b), air fuel ratio with knock and misfire limits of one engine (c), speed of one engine (d) per engine for the DP low operation**

# Configuration 2

## Case 1

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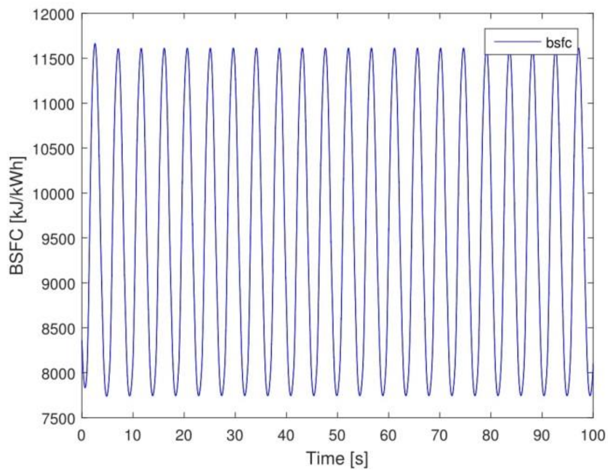


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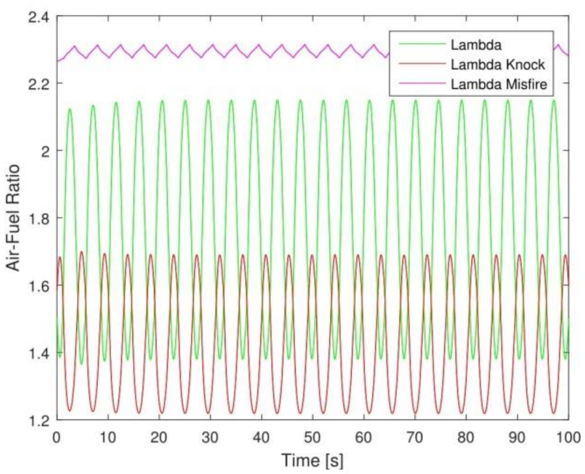


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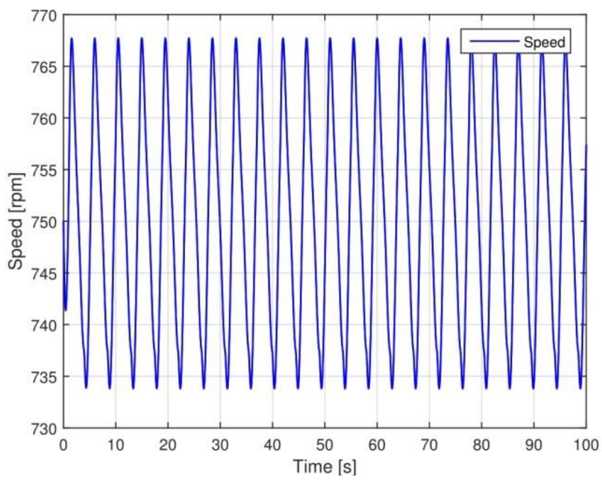
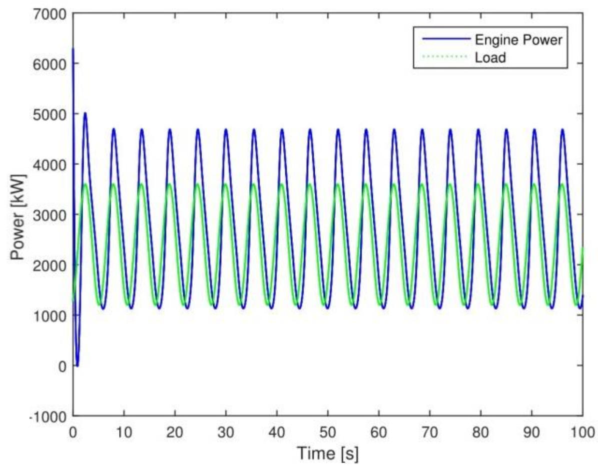



(d)

**Propulsion plant performance with per engine room power output (a), specific fuel consumption of one engine(b), air fuel ratio with knock and misfire limits of one engine (c), speed of one engine (d) per engine for the DP high operation**

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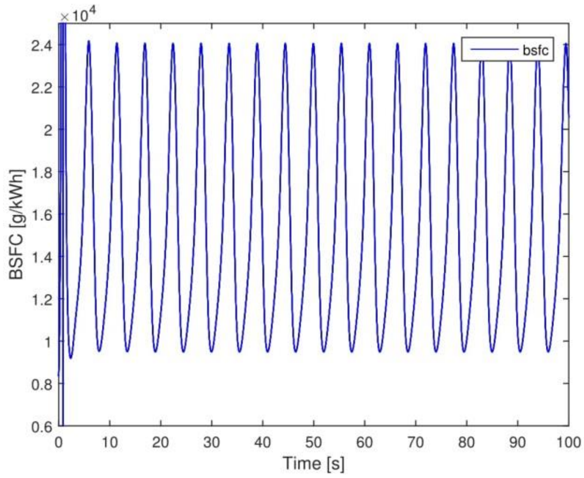


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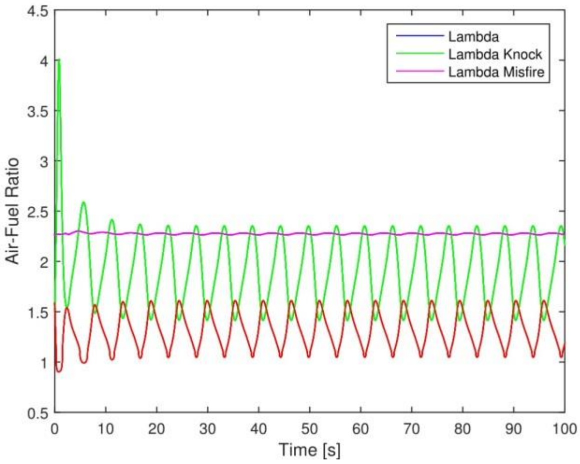


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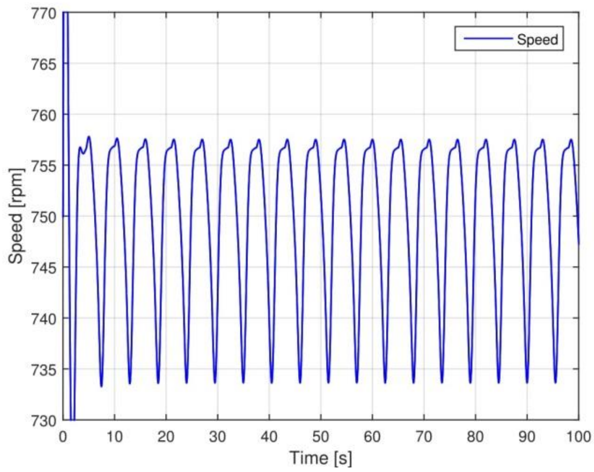
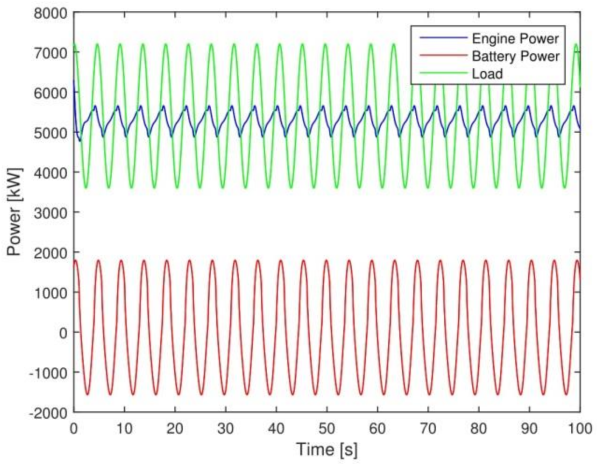



**(d)**

**Propulsion plant performance with per engine room power output (a), specific fuel consumption of one engine(b), air fuel ratio with knock and misfire limits of one engine (c), speed of one engine (d) per engine for the DP low operation**

# Case 2

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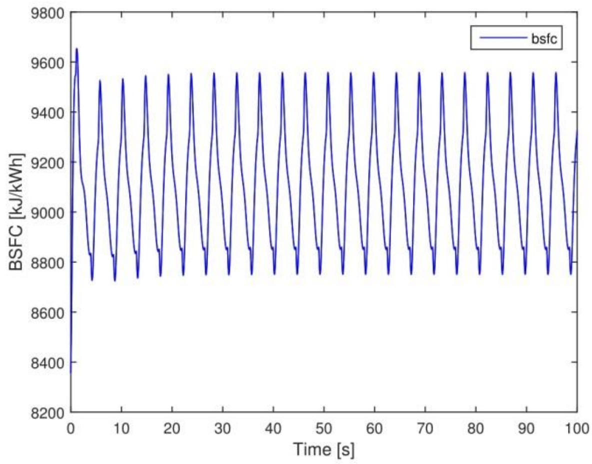


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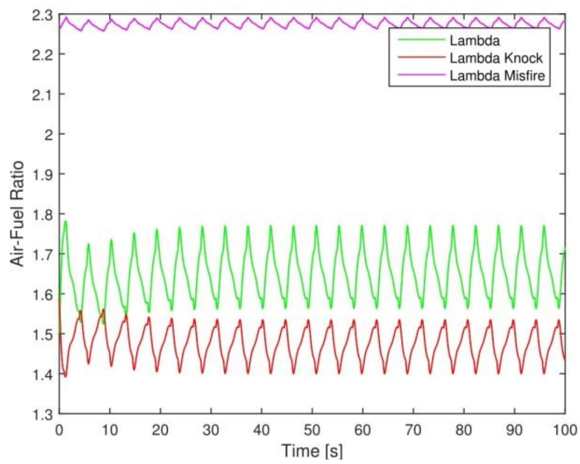


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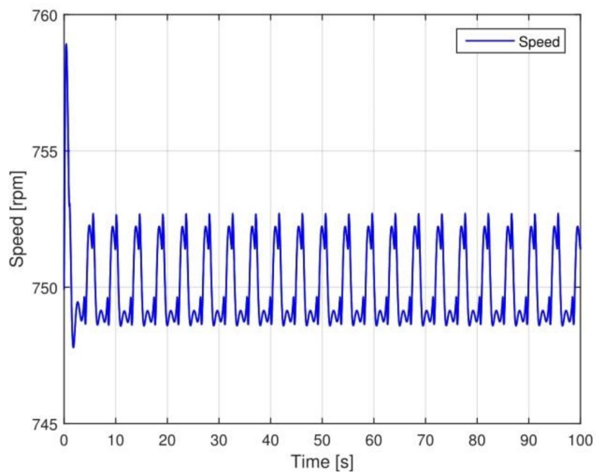
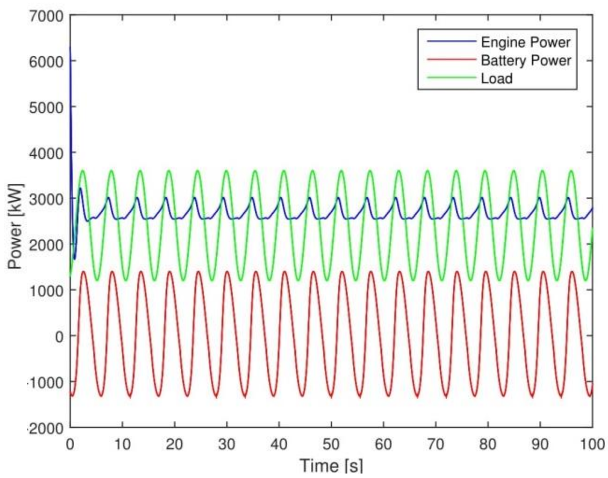



**(d)**

**Propulsion plant performance with per engine room power output (a), specific fuel consumption of one engine(b), air fuel ratio with knock and misfire limits of one engine (c), speed of one engine (d) per engine for the DP high operation**

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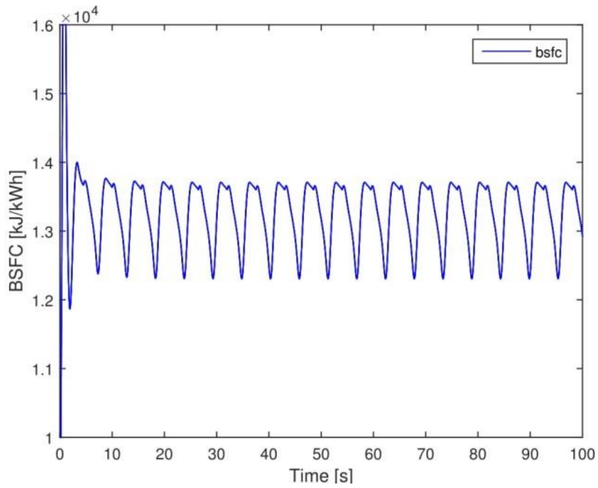


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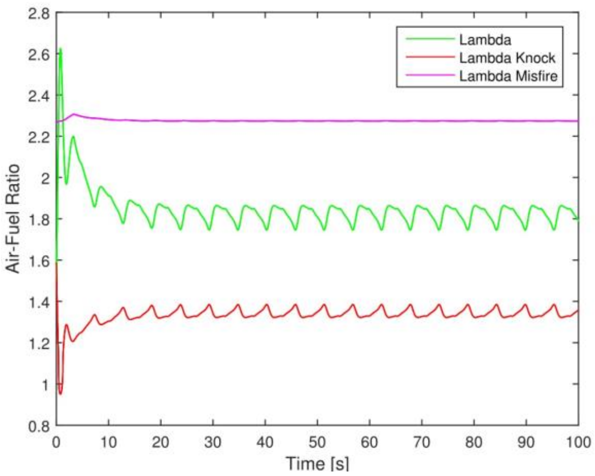


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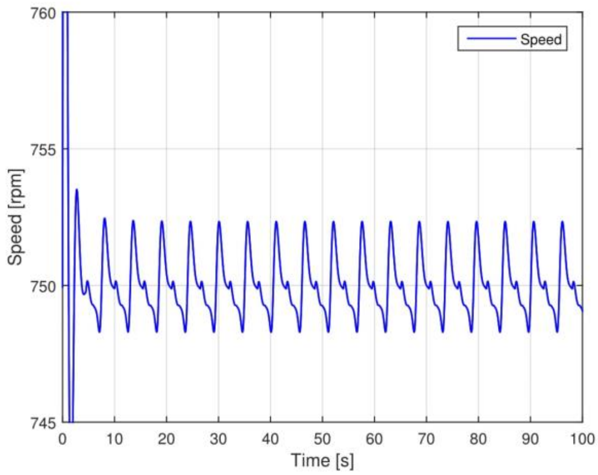
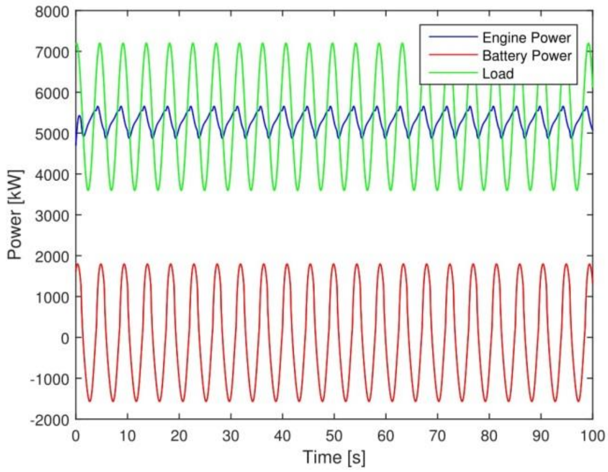


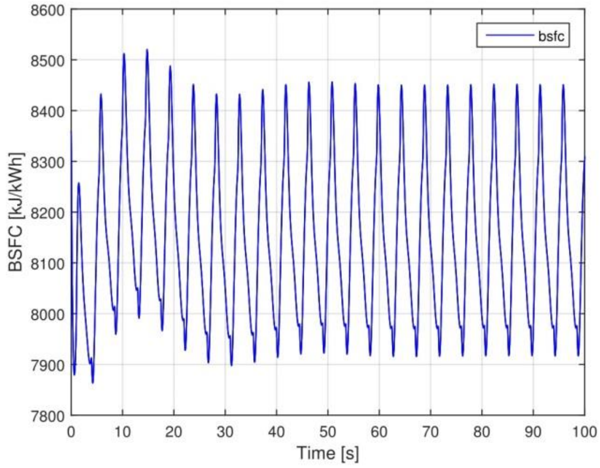

**(d)**

**Propulsion plant performance with per engine room power output (a), specific fuel consumption of one engine(b), air fuel ratio with knock and misfire limits of one engine (c), speed of one engine (d) per engine for the DP low operation**

# Case 3




**(a)**

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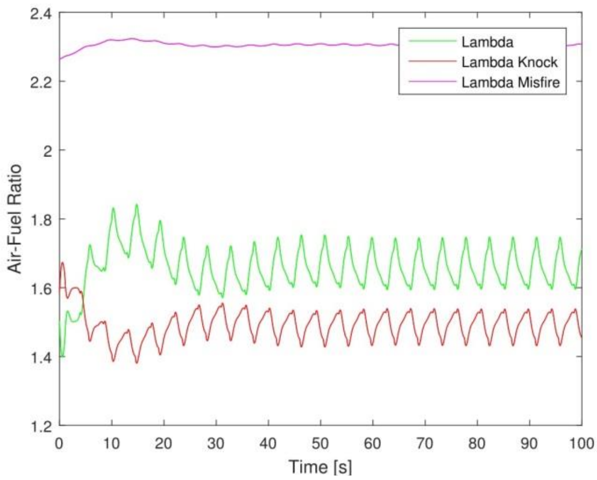


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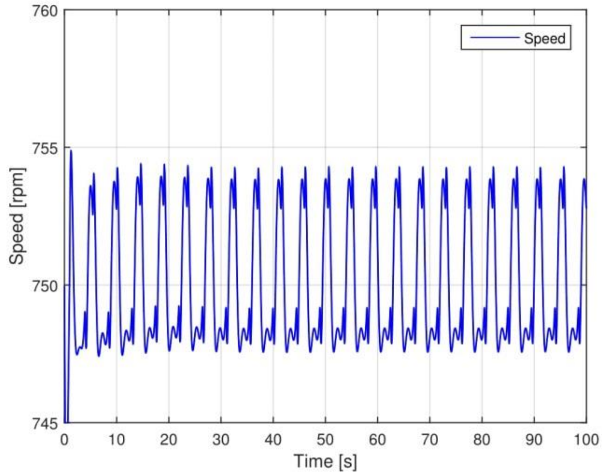
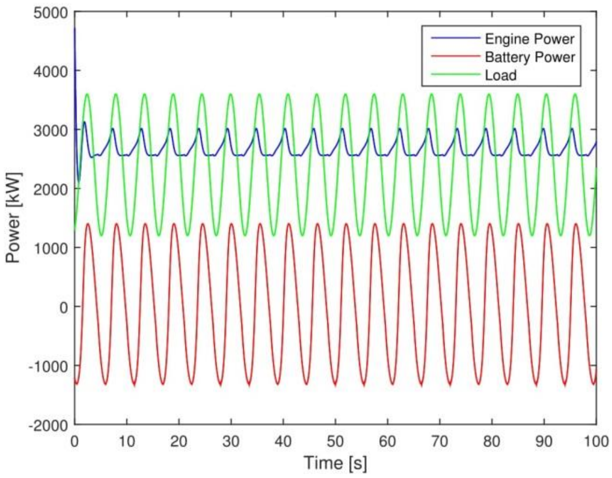
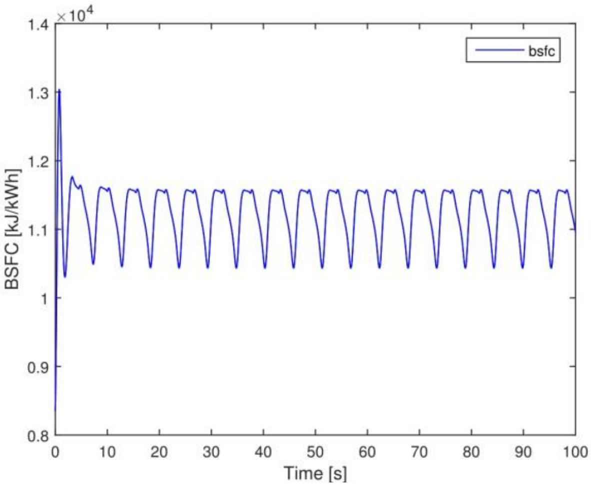



**(d)**

**Propulsion plant performance with per engine room power output (a), specific fuel consumption of one engine(b), air fuel ratio with knock and misfire limits of one engine (c), speed of one engine (d) per engine for the DP high operation**




**(a)**

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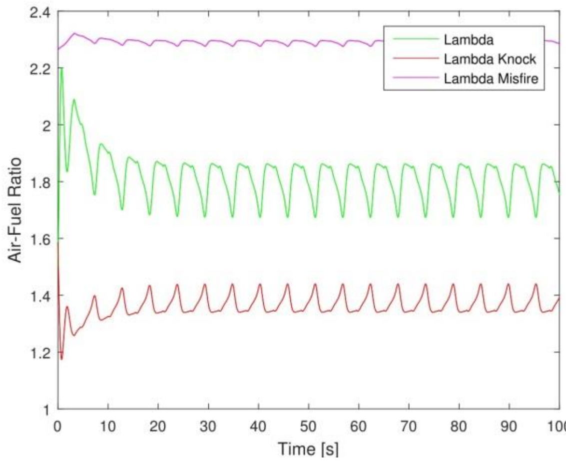
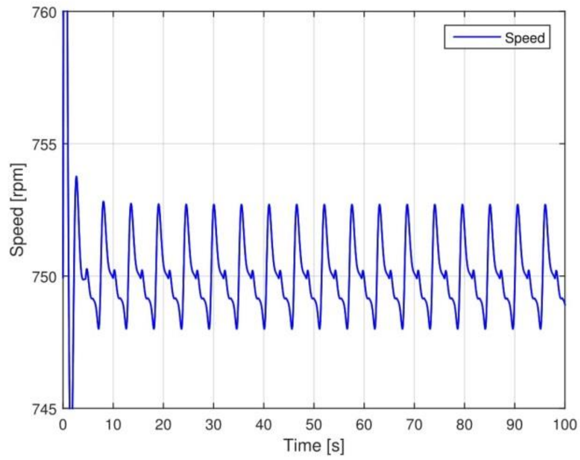



**(C)**

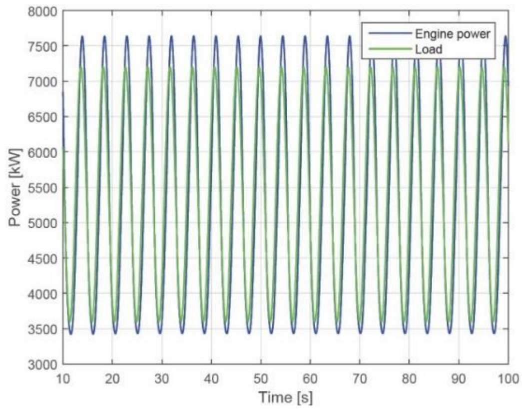



**(d)**

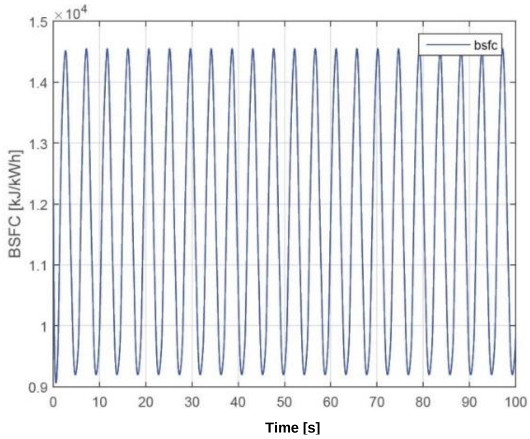
**Propulsion plant performance with per engine room power output (a), specific fuel consumption of one engine(b), air fuel ratio with knock and misfire limits of one engine (c), speed of one engine (d) per engine for the DP low operation**

# Configuration 3

## Case 1




(a)

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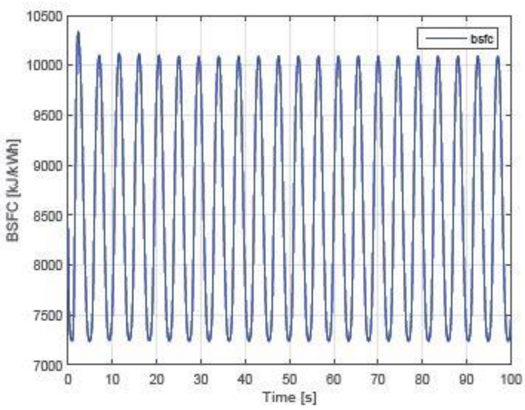
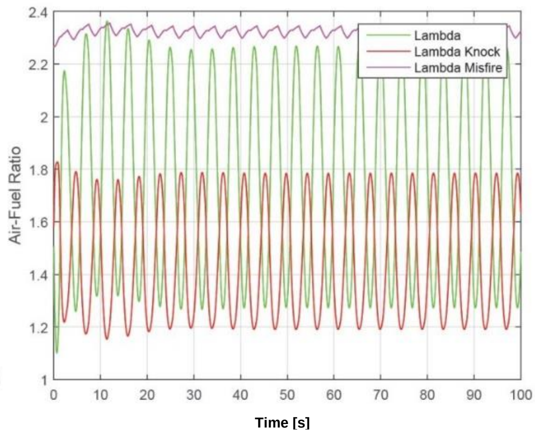
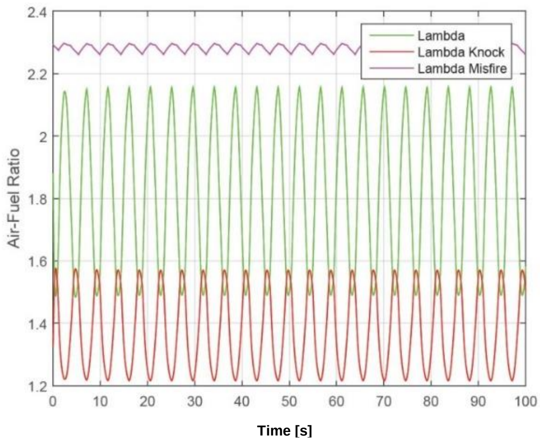



(c)




(d)

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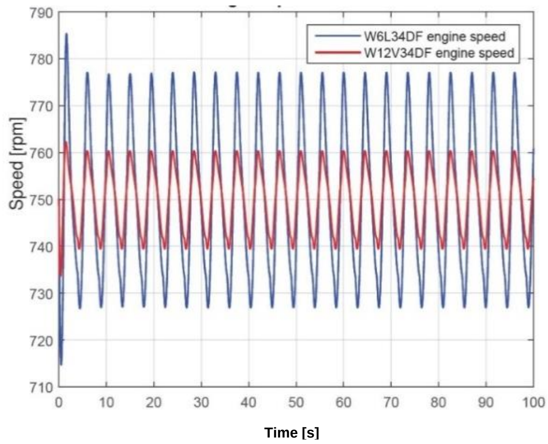
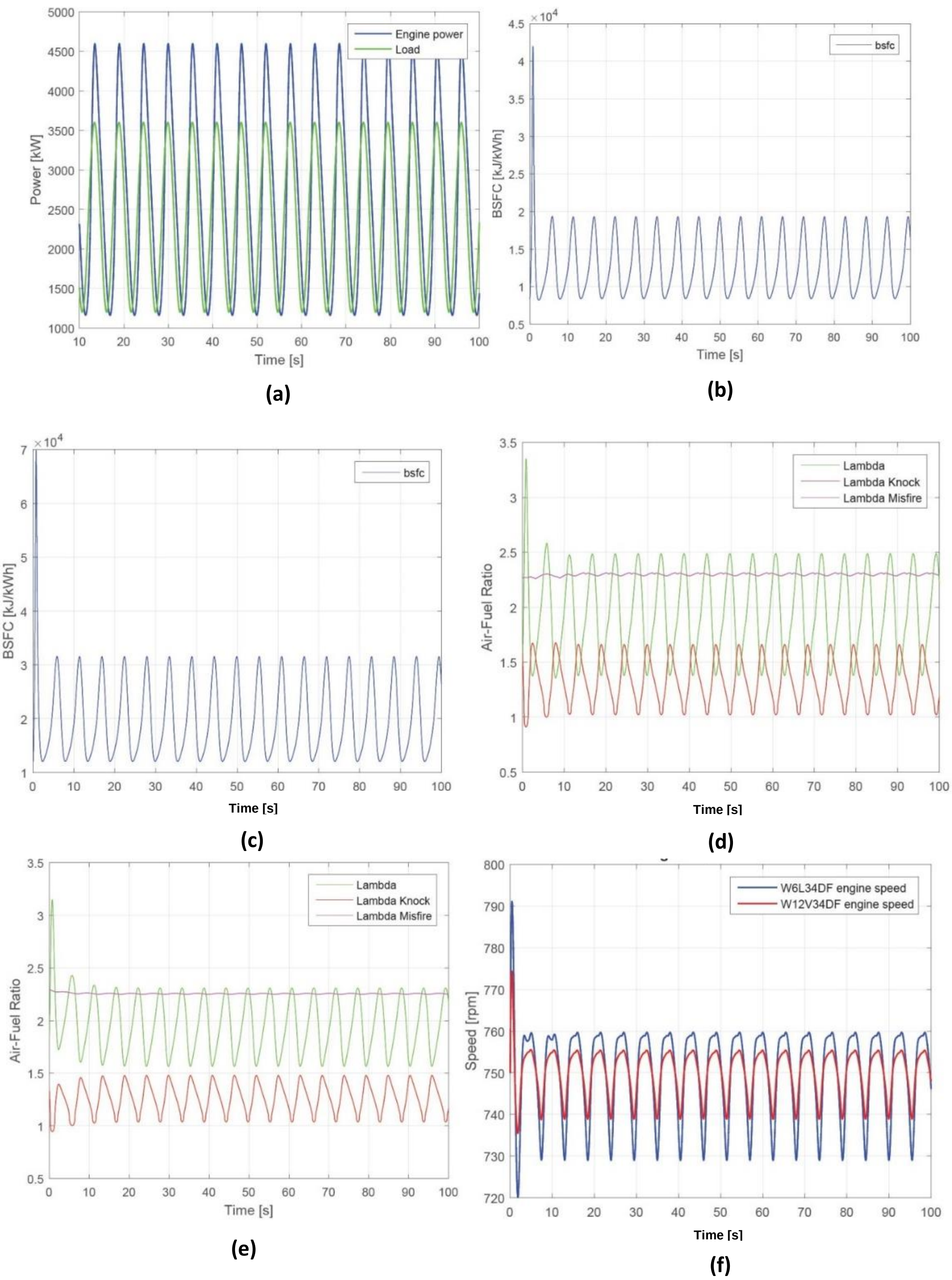


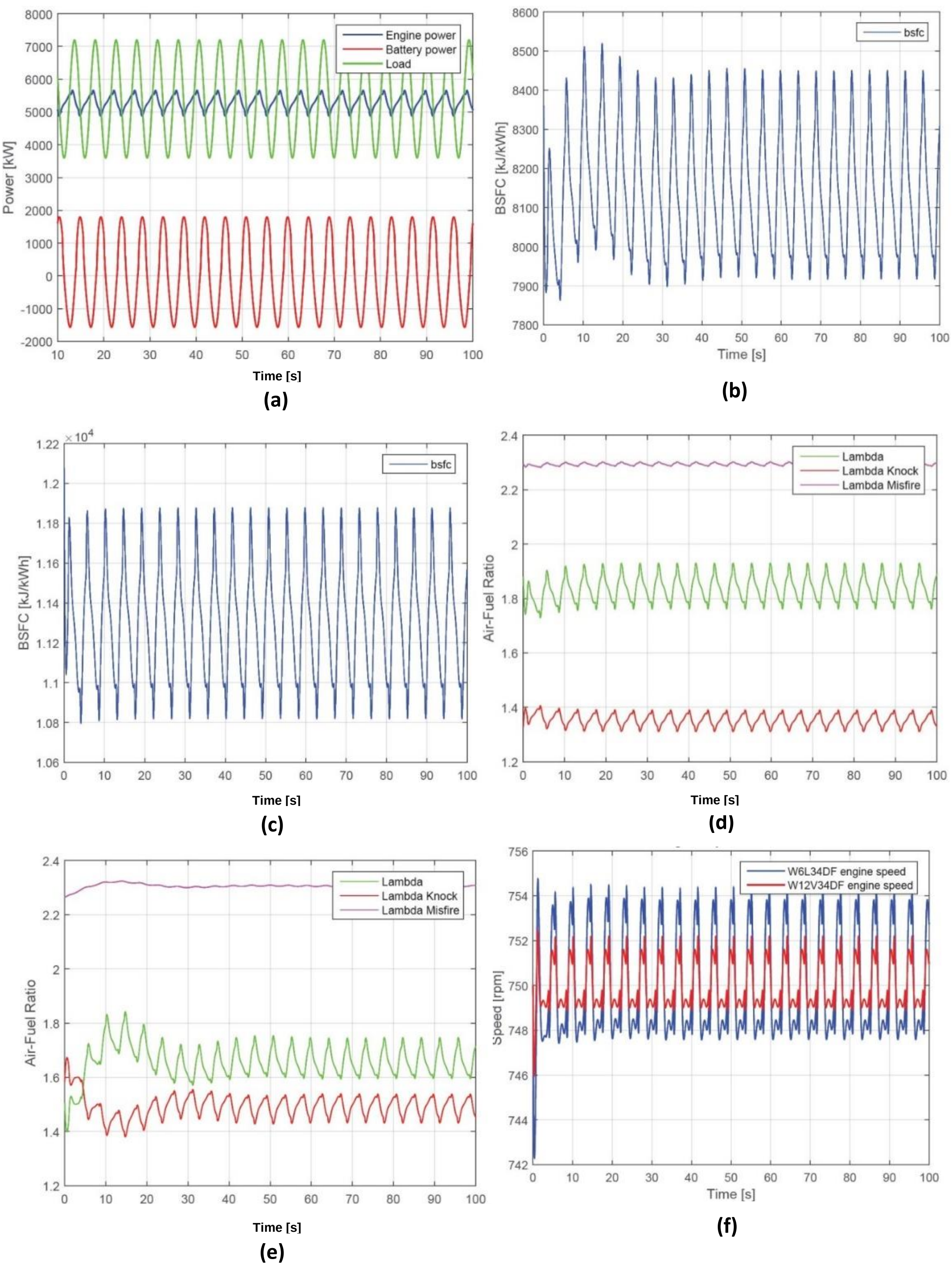

(f)

**Propulsion plant performance with per engine room power output (a), specific fuel consumption of W12V34DF engine(b), specific fuel consumption of W6L34DF engine(c), air fuel ratio with knock and misfire limits of W6L34DF engine (d), air fuel ratio with knock and misfire limits of W12L34DF engine (e), speed of W6L34DF and W12V34DF engine (d) for the DP high operation**

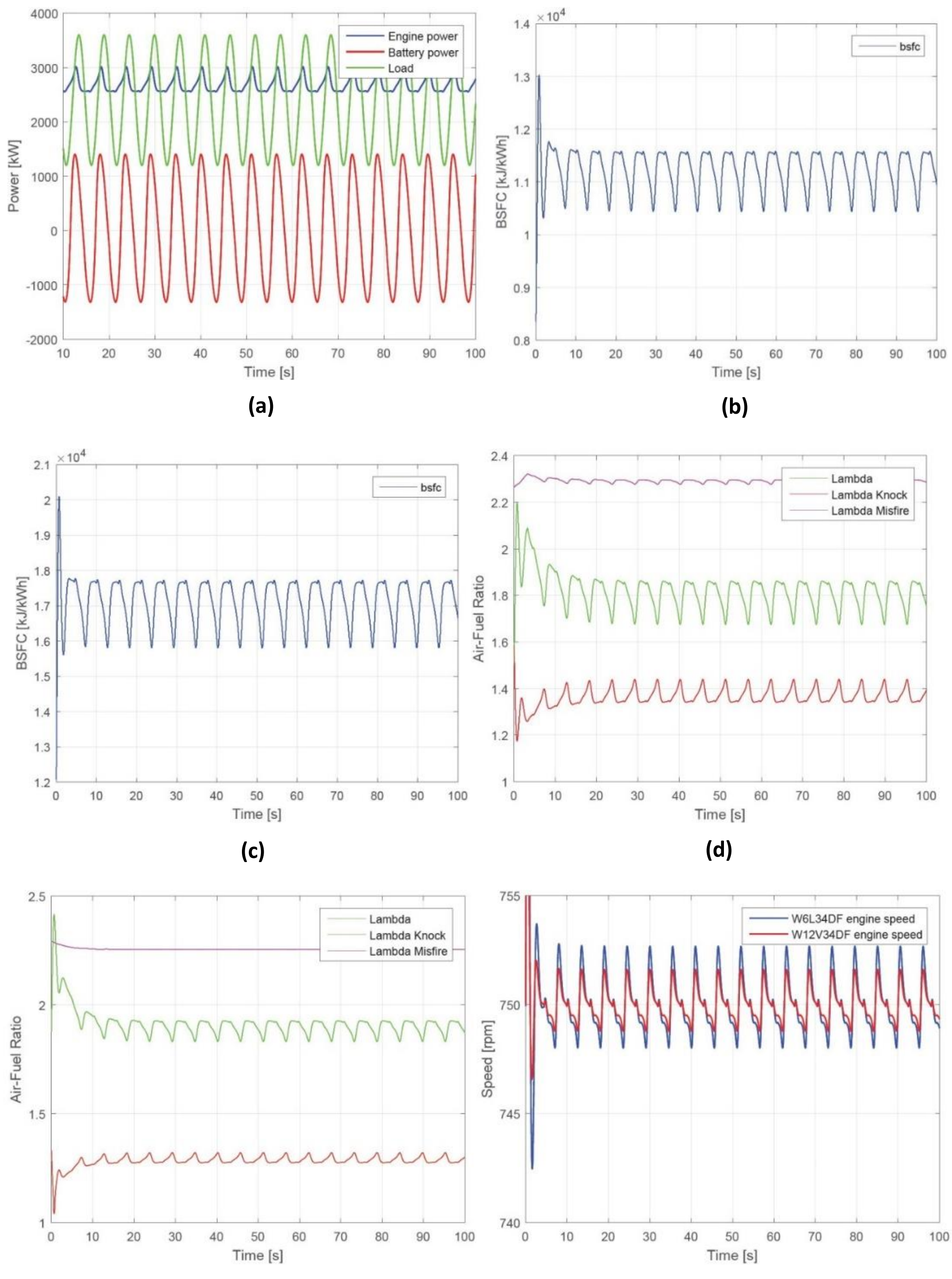



**Propulsion plant performance with per engine room power output (a), specific fuel consumption of W6L34DF engine(b), specific fuel consumption of W12V34DF engine(c), air fuel ratio with knock and misfire limits of W6L34DF engine (d), air fuel ratio with knock and misfire limits of W12L34DF engine (e), speed of W6L34DF and W12V34DF engine (d) for the DP low operation**

# Case 2

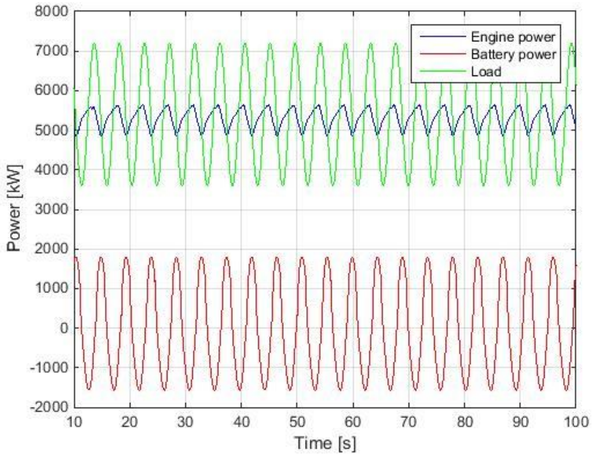



**Propulsion plant performance with per engine room power output (a), specific fuel consumption of W6L34DF engine(b), specific fuel consumption of W12V34DF engine(c), air fuel ratio with knock and misfire limits of W12V34DF engine (d), air fuel ratio with knock and misfire limits of W6L34DF engine (e), speed of W6L34DF and W12V34DF engine (d) for the DP high operation**

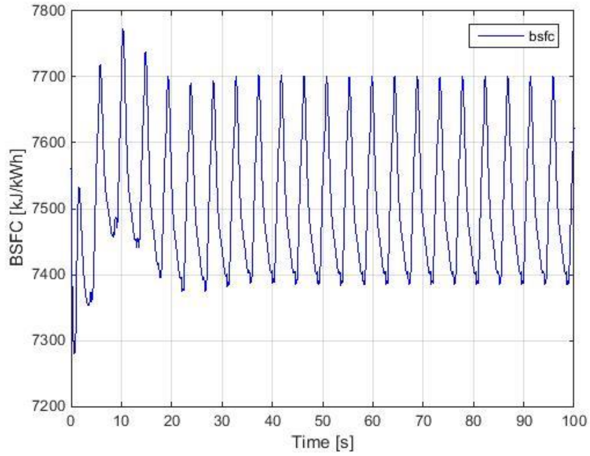



**Propulsion plant performance with per engine room power output (a), specific fuel consumption of W6L34DF engine(b), specific fuel consumption of W12V34DF engine(c), air fuel ratio with knock and misfire limits of W6L34DF engine (d), air fuel ratio with knock and misfire limits of W12V34DF engine (e), speed of W6L34DF and W12V34DF engine (d) for the DP low operation**

## Case 3




(a)

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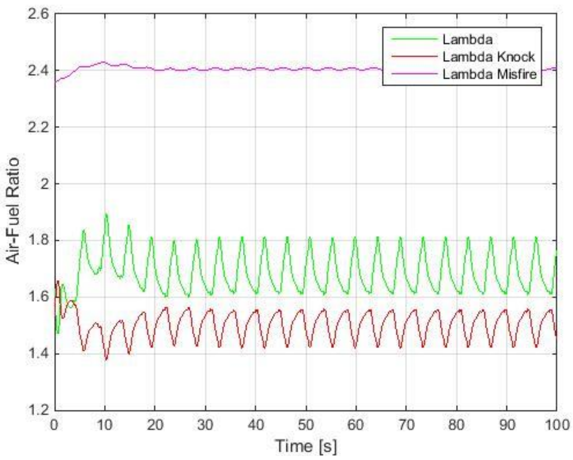
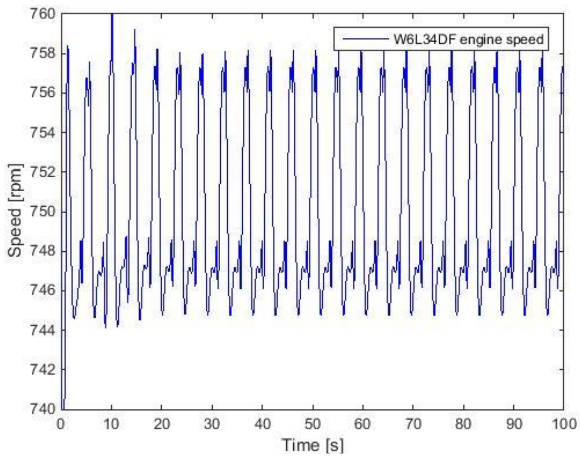
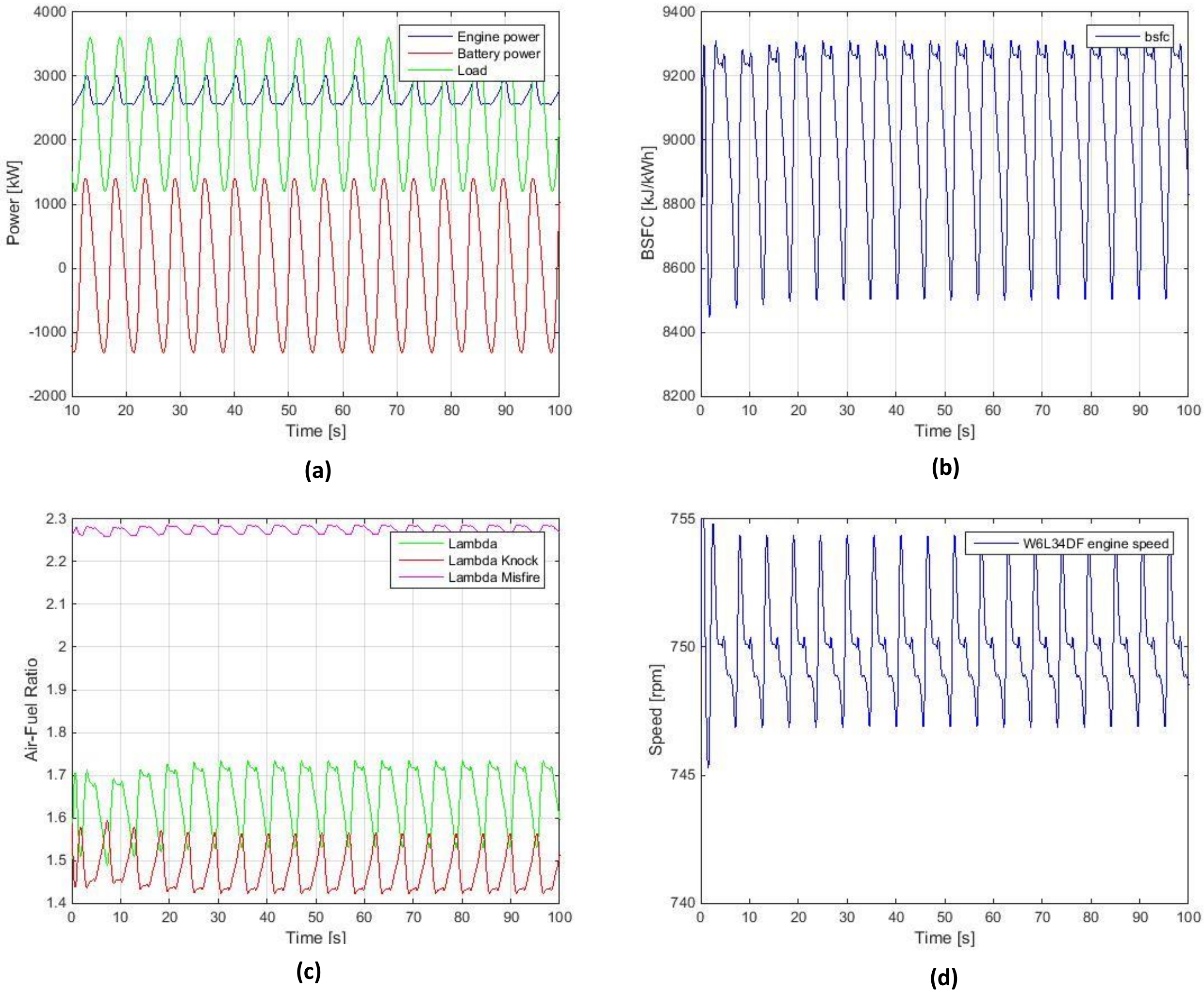



(c)




(d)

**Propulsion plant performance with per engine room power output (a), specific fuel consumption of one engine(b), air fuel ratio with knock and misfire limits of one engine (c), speed of one engine (d) per engine for the DP high operation**




**Propulsion plant performance with per engine room power output (a), specific fuel consumption of one engine(b), air fuel ratio with knock and misfire limits of one engine (c), speed of one engine (d) per engine for the DP low operation**

# C
# Model calculation

Table C.1: Configuration 1 calculation for fuel, green house gas and $SO_x$ emission

| **Configuration 1** | **Case 1** | | **Case 2** | | **Case 3** | |
|---|---|---|---|---|---|---|
| | DP high operation $\dot{m}_f[\frac{MJ}{s}]$ | DP low operation $\dot{m}_f[\frac{MJ}{s}]$ | DP high operation $\dot{m}_f[\frac{MJ}{s}]$ | DP low operation $\dot{m}_f[\frac{MJ}{s}]$ | DP high operation $\dot{m}_f[\frac{MJ}{s}]$ | DP low operation $\dot{m}_f[\frac{MJ}{s}]$ |
| Engine 1: W8L34DF | 4,607210384 | 3,287235684 | 4,45742249 | 3,295654544 | 5,808833114 | 3,921423942 |
| Engine 2: W8L34DF | 4,607210384 | 3,287235684 | 4,45742249 | 3,295654544 | 5,808833114 | 3,921423942 |
| Engine 3: W8L34DF | 4,607210384 | 3,287235684 | 4,45742249 | 3,295654544 | 0 | 0 |
| Engine 4: W8L34DF | 4,607210384 | 3,287235684 | 4,45742249 | 3,295654544 | 5,808833114 | 3,921423942 |
| Engine 5: W8L34DF | 4,607210384 | 3,287235684 | 4,45742249 | 3,295654544 | 5,808833114 | 3,921423942 |
| Engine 6: W8L34DF | 4,607210384 | 3,287235684 | 4,45742249 | 3,295654544 | 0 | 0 |
| Fuel Consumption [MJ] | 3.196 e6 | | 3.16957 e6 | | 2.58 e6 | |
| $CO_2$ emission [tons] | 179.0787 | | 177.5779 | | 144.9385 | |
| $SO_x$ emission [kg] | 0 | | 0 | | 0 | |

Table C.2: Configuration 2 calculation for fuel, green house gas and $SO_x$ emission

| **Configuration 2** | **Case 1** | | **Case 2** | | **Case 3** | |
|---|---|---|---|---|---|---|
| | DP high operation $\dot{m}_f[\frac{MJ}{s}]$ | DP low operation $\dot{m}_f[\frac{MJ}{s}]$ | DP high operation $\dot{m}_f[\frac{MJ}{s}]$ | DP low operation $\dot{m}_f[\frac{MJ}{s}]$ | DP high operation $\dot{m}_f[\frac{MJ}{s}]$ | DP low operation $\dot{m}_f[\frac{MJ}{s}]$ |
| Engine 1: W6L34DF | 3,460783288 | 2,466944308 | 3,342350272 | 2,471458074 | 3,997539368 | 2,79321731 |
| Engine 2: W6L34DF | 3,460783288 | 2,466944308 | 3,342350272 | 2,471458074 | 3,997539368 | 2,79321731 |
| Engine 3: W6L34DF | 3,460783288 | 2,466944308 | 3,342350272 | 2,471458074 | 3,997539368 | 2,79321731 |
| Engine 4: W6L34DF | 3,460783288 | 2,466944308 | 3,342350272 | 2,471458074 | 0 | 0 |
| Engine 5: W6L34DF | 3,460783288 | 2,466944308 | 3,342350272 | 2,471458074 | 3,997539368 | 2,79321731 |
| Engine 6: W6L34DF | 3,460783288 | 2,466944308 | 3,342350272 | 2,471458074 | 3,997539368 | 2,79321731 |
| Engine 7: W6L34DF | 3,460783288 | 2,466944308 | 3,342350272 | 2,471458074 | 3,997539368 | 2,79321731 |
| Engine 8: W6L34DF | 3,460783288 | 2,466944308 | 3,342350272 | 2,471458074 | 0 | 0 |
| Fuel Consumption [MJ] | 3.199 e6 | | 3.169 e6 | | 2.73 e6 | |
| $CO_2$ emission [tons] | 179.0787 | | 177.5779 | | 144.9385 | |
| $SO_x$ emission [kg] | 0 | | 0 | | 0 | |

Table C.3: Configuration 3 calculation for fuel, green house gas and $SO_x$ emission

| **Configuration 3** | **Case 1** | | **Case 2** | | **Case 3** | |
|---|---|---|---|---|---|---|
| | DP high operation $\dot{m}_f[\frac{MJ}{s}]$ | DP low operation $\dot{m}_f[\frac{MJ}{s}]$ | DP high operation $\dot{m}_f[\frac{MJ}{s}]$ | DP low operation $\dot{m}_f[\frac{MJ}{s}]$ | DP high operation $\dot{m}_f[\frac{MJ}{s}]$ | DP low operation $\dot{m}_f[\frac{MJ}{s}]$ |
| Engine 1: W6L34DF | 4,1773424 | 2,797974214 | 3,998965116 | 2,793601038 | 5,53227439 | 3,378367776 |
| Engine 2: W6L34DF | 4,1773424 | 2,797974214 | 3,998965116 | 2,793601038 | 5,53227439 | 3,378367776 |
| Engine 3: W12V34DF | 5,442111542 | 4,104071854 | 5,370018644 | 4,114975022 | 0 | 0 |
| Engine 4: W6L34DF | 4,1773424 | 2,797974214 | 3,998965116 | 2,793601038 | 5,53227439 | 3,378367776 |
| Engine 5: W6L34DF | 4,1773424 | 2,797974214 | 3,998965116 | 2,793601038 | 5,53227439 | 3,378367776 |
| Engine 6: W12V34DF | 5,442111542 | 4,104071854 | 5,370018644 | 4,114975022 | 0 | 0 |
| Fuel Consumption [MJ] | 2.165 e6 | | 2.1655 e6 | | 1.508 e6 | |
| $CO_2$ emission [tons] | 121.2984 | | 121.3253 | | 84.49269 | |
| $SO_x$ emission [kg] | 0 | | 0 | | 0 | |

Table C.4: PM emission calculation

| | **Configuration 1** | | | **Configuration 2** | | | **Configuration 3** | | |
|---|---|---|---|---|---|---|---|---|---|
| | Case 1 | Case 2 | Case 3 | Case 1 | Case 2 | Case 3 | Case 1 | Case 2 | Case 3 |
| DP high Power per engine[kWh] | 139,72 | 132,2566667 | 176,57 | 185,81 | 176,5933333 | 265,4466667 | 560,03 | 529,71 | |
| DP low power per engine [kWh] | 68,66666667 | 67,31 | 89,77666667 | 91,31666667 | 89,77666667 | 134,8 | 273,7333333 | 269,52 | 134,93 |
| Total [kWh] | 21155,2 | 20455,06 | 23761,26 | 37511,33333 | 36392,08 | 27333,06667 | 42258,1 | 40956,66 | 8365,66 |
| PM emission [kg] | 5,500352 | 5,3183156 | 6,1779276 | 9,752946667 | 9,4619408 | 7,106597333 | 3.662 | 3.549 | 2.175 |

# D
# Glossary

## List of Acronyms

**AC** alternating current

**AHV** Anchor handling vessel

**BMEP** break mean effective pressure

**BMS** battery management system

**BSFC** break specific fuel consumption

**BSFC** Break specific fuel consumption

**CNG** compressed natural gas

**DC** direct Current

**DF** Dual Fuel

**DOD** depth of discharge

**DGPS** Differential global positioning system

**DP** dynamic positioning

**ECA** emission controlled areas

**FES** flywheel energy storage

**FPSO** floating production storage and offloading

**GPS** Global positioning system

**IGF** International Gas Fuel Code

**IMO** International Maritime Organization

**ISO** International Organization of Standardization

**LI** lithium ion

**LNG** Liquified natural gas

**MCR** maximum continuous rating

**OSV** Offshore Supply Vessel

**PI** propotional-integral

**PM** particulate matter

**PSV** Platform supply vessel

**PWM** pulse width modultation

**ROV** remotely operated vehicles

**rpm** rotations per minute

**rps** rotatation per second

**SFC** specific fuel consumption

**SOC** state of charge

**UPS** Uninterrupted power source

**VSC** voltage source conveter

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# List of Figures

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