Modelling, Design and Energy Management of a Hybrid Electric Ship – A Case Study

by

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Bachelor of Engineering, Zhejiang University City College, 2014

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Supervisory Committee

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Abstract

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The widely-used passenger and car ferries, sailing regularly and carrying heavy loads, form a unique type of marine vessel, providing vital transportation links to the coastal regions. Modern ferry ships usually are equipped with multiple diesel engines as prime movers. These diesel engines consume a large amount of marine diesel fuel with high fuel costs, and high emissions of greenhouse gas (GHG) and other harmful air pollutants, including CO_2, HC, NO_x, SO_2, CO, and PM. To reduce fuel costs and the harmful emissions, the marine industry and ferry service providers have been seeking clean ship propulsion solutions.

In this work, the model-based design (MBD) and optimization methodology for developing advanced electrified vehicles (EV) are applied to the modelling, design and control optimizations of clean marine vessels with a hybrid electric propulsion system. The research focuses on the design and optimization of the hybrid electric ship propulsion system and uses an open deck passenger and car ferry, the MV Tachek, operated by the British Columbia Ferry Services Inc. Canada, as a test case. At present, the ferry runs on the Quadra Island – Cortes Island route in British Columbia, Canada, with dynamically changing ocean conditions in different seasons over a year.

The research first introduces the ship operation profile, using statistical ferry operation data collected from the ferry's voyage data recorder and a data acquisition system that is specially designed and installed in this research. The ship operation profile model with ship power demand, travelling velocity and sailing route then serves as the design and control requirements of the hybrid electric marine propulsion system. The development of optimal power control and energy management strategies and the optimization of the powertrain architecture and key powertrain component sizes of the ship propulsion system are then carried out. Both of the series and parallel hybrid electric propulsion architectures have been studied. The sizes of crucial powertrain components, including the diesel engine and battery energy storage system (ESS), are optimized to achieve the best system energy efficiency. The optimal power control and energy management strategies are optimized using dynamic programming (DP) over a complete ferry sailing trip.

The predicted energy efficiency and emission reduction improvements of the proposed new ship with the optimized hybrid propulsion system are compared with those of two benchmark vessels to demonstrate the benefits of the new design methodology and the optimized hybrid electric ship propulsion system design. These two benchmarks include a conventional ferry with the old diesel-mechanical propulsion system, and the Power Take In (PTI) hybrid electric propulsion systems installed on the MV Tachek at present. The simulation results using the integrated ship propulsion system model showed that the newly proposed hybrid electric ship could have 17.41% fuel saving over the conventional diesel-mechanical ship, and 22.98% fuel saving over the present MV Tachek. The proposed optimized hybrid electric propulsion system, combining the advantages of diesel-electric, pure electric, and mechanical propulsions, presented considerably improved energy efficiency and emissions reduction. The research forms the foundation for future hybrid electric ferry design and development.

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Acknowledgments

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Dedication

I would predominantly like to thank Dr. Zuomin Dong for the guidance, continued support, and good faith. I want to dedicate my Master's thesis work to my family, who have supported me over the past years. I could not have made it without their continuous encouragement and supports.

Glossary of Acronyms and Abbreviations

AC	Alternating Current
A-ECMS	Adaptive Equivalent Consumption Minimization Strategy
APD	Approximate Dynamic Programming
BC	British Columbia
BC Ferries	British Columbia Ferry Services Inc
BSFC	Brake-Specific Fuel Consumption
CAN	Controller Area Network
CAT	Caterpillar Inc.
CFD	Computational Fluid Dynamics
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CS	Charge Sustaining
DA	Data Acquisition
DC	Direct Current
Die-Gen	Diesel Generator
DIRECT	Dividing Rectangles Global Optimization Algorithm
DP	Dynamic Programming
ECMS	Equivalent Consumption Minimization Strategy
e-CVT	Electronic Continuously Variable Transmission
EGO	Efficient Global Optimization Algorithm
EMS	Energy Management Strategy
ESS	Energy Storage System
EV	Electric Vessel
G	Generator

GA	Generic Algorithm
GHG	Green House Gas
GPS	Global Positioning System
GWO	Grey Wolf Optimization Algorithm
HC	Hydrocarbons
HESS	Hybrid Energy Storage System
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
IMO	International Maritime Organization
LAN	Local Area Network
LHD	Load Haul Dump
LHV	Lower Heating Value
M	Motor
MBD	Model-Based Design
MECH	Diesel Mechanical
Modbus TCP/IP	Modbus Communications Protocol Based on Transmission Control Protocol and The Internet Protocol
MPC	Model Predictive Control
MPS	Minimum Population Search Method
MSSR	Multi-Start Space Reduction Method
NFE	Number of Function Evaluations
NMEA	National Marine Electronics Association
NO_X	Nitrogen Oxide
NREL	National Renewable Energy Laboratory
OSU	Ohio State University

PEV	Pure Electric Vehicle
PHEV	Plug-In Hybrid Electric Vehicle
PMP	Pontryagin's Minimum Principle
PNGV	Partnership for A New Generation Of Vehicles
PSO	Particle Swarm Optimization Algorithm
PTI	Power Take In
PTO	Power Take Off
RB	Rule Based
SOC	Stat of Charge
SO_X	Sulfur Dioxide
SQP	Sequential Quadrat Programming
STBD	Starboard
TECHSOL	Techsol Marine
US-DOE	United States Department of Energy
UVic	University of Victoria
VDR	Voyage Data Recorder
VFD	Variable-Frequency Drive

Chapter 1 INTRODUCTION

1.1. The benefit of Hybrid Electric Propulsion

Today, a vast amount of energy is consumed to support our modern life, from heating, air conditioning, lighting to communication and transportation, and our contemporary society is primarily fossil-fuel driven. However, the endless consumption of the diminishing fossil fuel caused severe environmental impacts and concerns around the world, driving legislators and organizations to introduce more and more strict laws and regulations [1]–[4]. Different organizations have introduced various guidelines and targets on the reduction of GHG emissions, particularly for transportation applications, including vehicles and marine vessels.

Researchers and industries are searching for the path to a greener future, including using renewable energy, alternative fuels, and developing innovative technology to reduce GHG emissions and other harmful pollutions. Hybrid electric propulsion is one of the technologies that have the potential to improve energy efficiency and reduce emissions. Typically, a hybrid electric vehicle (HEV) can improve fuel economy by about 20%, compared to a conventional vehicle that is solely powered by an internal combustion engine (ICE). A plug-in HEV (PHEV) could further improve energy efficiency and reduce emissions, due to the higher potential to allow its mechanical and electric drives to operate optimally, and the partial use of renewable energy. The improvement is largely due to its larger electric drive and high energy density Li-ion battery energy storage system (ESS), and the ability to use electrical energy acquired from the power grids and generated from renewable energy sources. For vehicles powered by a diesel engine, the hybrid-electric propulsion system provides a 50% emission reduction on nitrogen oxides reduction, 20% on carbon monoxide reduction and more than 65% fuel savings according to National Renewable Energy Laboratory (NREL) [5]. The social, environmental, and economic benefits of using hybrid-electric propulsion systems have been studied for more than 30 years. Still, the broad application of this technology is mostly limited to the automotive industry. With the increasing concerns about the environment and cost, those technologies become more attractive to the marine industry. The following subsections will illustrate the fundamental techniques and components in HEVs and investigate their potentials to hybrid electric ships.

1.2. Development of Hybrid Electric Vehicles

With the energy efficiency and emission reduction advantage, HEVs and PHEVs represent technology evolution for ground transportation over conventional ICE vehicles with a sole mechanical drive. Typically, a PHEV has an on-board electric ESS, allowing the vehicle to operate as a pure electric vehicle (PEV) over a specific driving range and operate as an HEV with the ICE to run more efficiently. The best trade-off between energy efficiency and performance becomes critical, demanding the development of advanced power control and energy management algorithms. Ferdinand Porsche developed the first hybrid electric car, Lohner-Porsche, in 1901, and hybrid electric vehicles became widely available and mass-produced in 1997 when the Toyota Prius was released. Many hybrid electric powertrain architectures and their control algorithms have been well studied. The HEVs and PHEVs combine the propulsion modes of conventional ICE-powered vehicles and PEVs using ICE and motors/generators to propel the vehicles with dynamically changing power distribution between them. The commonly used powertrain architectures include:

- Serial architecture
- Parallel architecture
- Power-split or Serial/parallel architecture

The use of different types of transmissions, electric motors, and generators, and ICEs and the orders of their arrangements lead to many subdivisions of each of these three powertrain architectures.

In a series hybrid vehicle, the vehicle is solely propelled by a large electric motor, while the ICE either operates at its highest efficiency to drive the generator or turns off. The electric power produced by the engine-generator is used to propel the vehicle or to charge the ESS, determined by the state of charge (SOC) of the battery ESS. The gain of energy efficiency is due to the ICE's high operation efficiency, despite the vehicle power demand. However, the powertrain suffers unavoidable energy conversion losses and becomes less efficient for a vehicle operating at a constant speed with a steady power load.

A parallel hybrid vehicle, such as the Honda Civic Hybrid and Chevy Malibu 2013, propels the vehicle using its electric motor, ICE, or a combination of both. The powertrain uses the engine to drive the vehicle and the generator when there is surplus power, allowing the ICE to operate primarily, not entirely, over its most efficient speed and torque region. The ICE and motors are coupled to the final drive through some mechanism, such as clutch, belt. The motor can work as a generator so that the regenerating power from braking can be partially recovered.

A series-parallel powertrain architecture, also known as power-split, is the most successful architecture in the midsize hybrid vehicle market. This architecture has the advantages of both parallel and series powertrains by supporting both series and parallel modes. Toyota Prius and UVic EcoCAR2 that has been developed at the University of Victoria belong to this family.

The primary advantage of a power-split architecture is due to its more degrees of freedom for powertrain operation control in comparison to the series or parallel powertrain architectures, leading to improved powertrain system efficiency and vehicle drivability. Meanwhile, this powertrain architecture is more complex, requiring advanced energy management strategy (EMS) and optimal control to achieve the energy efficiency potential. The optimal EMS algorithm needs to determine the operation mode and power split level dynamically among all contributing power sources.

Numerous types of EMS have been developed for HEVs and PHEVs. A PHEV, due to its ability to operate as a PEV, further require different EMS. Researchers at Argonne National Lab compared the different hybrid electric powertrain configurations, including power-split with a small ESS and series powertrain with a large ESS, using different control strategies.

Typically, the commonly used EMS can be classified into two categories: optimization-based and rule-based power control and energy management strategies, as presented in Figure 1.

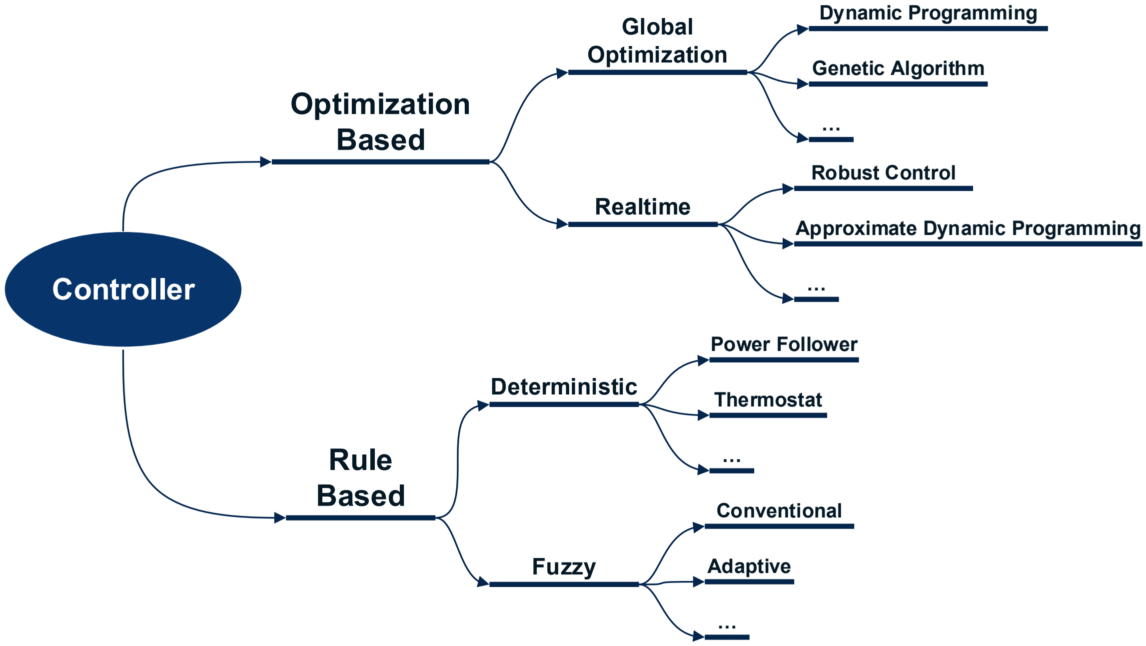

Figure 1 Power Control and Energy Management Strategy Categories

1.3. Key Enabling Technology for Hybrid Electric Propulsion

1.3.1. Advanced Hybrid Electric Propulsion System

Similar to HEVs/PHEVs, the hybrid electric marine propulsion system combines an ICE with an electric drive to achieve a better fuel economy and/or better performance than a conventional pure mechanical propulsion system. An onboard ESS stores energy provisionally, breaking the linear relationship between the fuel convertor and propulsion power demands. These features add more flexibility to the system, and advanced power control and energy management controller are needed to manage the power split ratio between the mechanical and electrical drives. This controller also monitors the ship propulsion state, such as ESS SOC, etc. In a conventional, mechanical drive propulsion system or pure electric propulsion system, a simple rule-based or even a human-operated system controller is used, since the power generated from the prime movers is linear to the propulsion power demand. However, prime movers in an ICE hybrid electric propulsion system operate differently with more flexibly for operation control. The ESS serves as an energy buffer that can absorb and store the extra power generated by the prime mover for later use. The power generated by prime movers is no longer directly proportional to the required propulsion power at each instance of time. Advanced power control and an EMS controller is needed to manage the power flow and energy distribution properly. The typical power control and energy management strategy can be divided into two categories: rule-based and optimization-based power control and energy management strategy.

1.3.2. Rule-Based Power Control and Energy Management Strategy

a) Deterministic Rule-based Power Control and Energy Management Strategy

The rule-based energy management strategy that applies to the series HEV is straightforward, similar to a bang-bang control rule. This method keeps the variation of battery ESS SOC within an allowed range by turning the engine on and off periodically.

The *power follower control strategy* is a popular strategy for a hybrid electric propulsion system power control and energy management. This approach forces the engine output torque to follow a predetermined optimal engine operation curve to provide the required propulsion power, and the EM fills the gap between the optimal torque and required torque. Those rules can be summarized as follows:

- Use the electric motor only (in EV mode) when the vehicle runs under a specific speed, u.
- Operate the engine at an optimal operation point with a specific speed and torque output, using the electric machine (acting as a motor or generator) to fill the gap or absorb the surplus of the power generated by the engine and the required propulsion power.
- Use the electric motor to assist the propulsion if the propulsion power demand is higher than the allowed maximum engine power at the operating speed.
- Increase the engine power demand so that the ESS can be charged via the generator if the SOC of the ESS is below the allowed threshold.
- Charge the battery ESS using regenerative power if the brake signal is triggered. The vehicle regenerative braking usually does not apply to ship propulsion.

Following the power follower control strategy, the performance of hybrid electric propulsion system can be improved considerably over the on and off only thermostat control strategy, due to the use of the engine optimal operation curve. However, the efficiency of the complete powertrain and the overall system efficiency under different loads have not considered and optimized.

b) Fuzzy Rule-based Power Control and Energy Management Strategy

Fuzzy sets and fuzzy logic allow us to produce approximate solutions with some level of uncertainty so that the problem can be represented in a form that human operators can understand. Fuzzy logic can be used to design a controller that uses experts' knowledge and experience, making it easier to apply the human experience while developing the controller. A fuzzy controller consists of four components: fuzzification, inference engine, defuzzification, and fuzzy rule base. The system parameters are converted back and forth into fuzzy variables to support the inference using fuzzy rules. The inference engine performs inferencing upon fuzzified inputs to produce a fuzzy output. The fuzzy rule base contains the knowledge and experience of human experts.

PHEVs and HEVs are typically a nonlinear, multi-domain, and time-varying complex system. It usually is hard to determine the exact changeover point and the timing for the motor to kick in. Numbers of fuzzy controllers for HEVs and PHEVs have been developed. Typically, those fuzzy controllers consist of few inputs (acceleration pedal stroke and the engine speed) and one output (normalized torque demand). The result shows that the fuzzy-logic based management strategy is robust, able to reduce harmful emissions and maintain the battery SOC within a specified range in the charge sustaining (CS) mode.

1.3.3. Optimization Based Power Control and Energy Management Strategy

The minimization of the fuel consumption or emissions of a hybrid vehicle is an optimization problem. The rule-based energy management strategy is deduced from human experience and knowledge and is not optimized. By its very nature of the PHEVs operation conditions, a globally optimal solution is hard to achieve online in real-time. However, for real-time optimal power control and energy management, an optimal local solution is acceptable.

a) Real-time Optimal Power Control and Energy Management

Typically, a rule-based energy management strategy relies on current and historical driving conditions to perform real-time control. While the generation of a real-time optimization-based energy management strategy is challenging since it typically relies upon entire driving cycle information to produce the unique globally optimal solution. Several different types of control algorithms have been developed.

In recent years, model predictive control (MPC) received increasing attention for the HEV application [6]–[8]. As an advanced method of process control, MPC usually uses a linear empirical model to predict system behaviour and control the operations of the system under given constraints over a finite time-horizon at present. By sliding the time-horizon window into the future, MPC can anticipate coming events and take control actions accordingly. The MPC used the current plant measurements, dynamic state, plant model, operation constraints, and a cost function that needs to be optimized to induce a sequence of control actions. Some researcher also combines MPC with the Markov chain to predicate the driver's behaviour and shows performance close to MPC with full knowledge of the entire driving profile for real-time driving.

However, the most successful and widely studied real-time control strategy that applies to HEVs and PHEVs applications is the Equivalent Consumption Minimization Strategy (ECMS) and Pontryagin's Minimum Principle (PMP).

ECMS reduces the global optimization problem into a local minimization problem at each operation time by only feeding the information about the past. The idea of ECMS can be summarized as the following. In the charge sustaining (CS) mode of a PHEV, the ESS is treated as a buffer of the engine power since the energy is produced from the engine and will not be refilled externally from the power grid. The energy in this buffer that is used during the vehicle operation can only be replenished in advance or later using an external energy source or regenerating braking. The comparable fuel consumption is associated with the use of stored energy from the battery, which can be positive or negative, and the engine should be independently to work at its highest efficiency. The actual fuel consumption of the ICE and the comparable fuel consumption from the ESS form the equivalent fuel consumption, and its value could be higher or lower than the instantaneous fuel consumption from the ICE.

As described above, an ECMS can achieve a suboptimal solution in real-time control by selecting a suitable factor as long as the driving cycle is given, and the equivalent factor is adequately calibrated offline. Thus, future driving information is needed. However, the optimal factor for different driving cycles is hard to achieve; and in some research, and adaptive ECMS (A-ECMS) is introduced since a priori knowledge of the driving cycle is hard to provide. The optimal control problem is thus transformed into a data mining or pattern recognition problem. The idea behind the A-ECMS is to use collected information to predict future driving patterns and to use pre-defined control parameters to tune and optimize the control parameters for a globally quasi-optimal control solution. The approach can produce a quasi-optimal global solution in real-time applications due to its ability to predict the near future, but not the entire trip.

Researchers developed several types of adaptation techniques [9], including:

a) Driving pattern recognition-based A-ECMS
b) Driving cycle prediction-based A-ECMS

Researchers at Ohio State University (OSU) compared three energy management strategies over various driving cycles, including DP, optimal ECMS, A-ECMS. Optimal ECMS refers to an ECMS that using a pre-optimized equivalence factor. Those results indicate that the A-ECMS can achieve an accurate result close to DP.

b) Global Optimization-based Power Control and Energy Management Strategy

Dynamic programming is a widely used method for solving the optimal control problem. It is a numerical method that finds a globally optimal solution by operation backward in time. However, it can not apply to a real vehicle since this method requires the entire driving cycle information in advance, and the algorithm needs to be driven backward.

Consider the vehicle operation condition in the form of:

$$x_{k+1} = f\ (x_k, u_k) \tag{1-1}$$

where k is an integer number, says k = 0, 1, 2, …, let u_k be the control variable, which means the instantaneous fuel consumption and ESS power at time k. Next, a cost function can be obtained, and this optimization problem is transformed into a minimization problem.

$$\min J(x_0, u) \tag{1-2}$$

where x_0 is the initial vehicle condition, and u is a vector that contains all the control variables.

The limitations of the DP include: a) limited to an off-line approach, b) requiring huge computation resources, and c) limited to discrete control variables for a continuous physical system.

Pontryagin's Minimum Principle (PMP) has recently received the most attention. The idea behind the PMP is similar to A-ECMS. However, it doesn't require multiple equivalence factors, since the difference among operation conditions are implicitly taken into account in the evaluation of quantity.

1.4. Motivations of Hybrid Electric Propulsion for Marine Vessels

Today the development of technology and the increasing concern of the environment leads to the transformation from conventional vehicles to pure (or hybrid) electric vehicles on land vehicle applications. However, nowadays, most of the modern ships are only equipped with diesel engines as their prime mover due to their operating simplicity and matured technology. Electrifying the propulsion system of marine fleets has a long history. The first electric ship was built more than 150 years ago right after the first electric motor was invented in 1838 [10]. The electrical propulsion system can increase energy efficiency by reducing hydrodynamic losses. The improvement is achieved by using a variable speed electric drive to run the EM driven propellers at different speeds for different operation conditions and to optimize the power plant configuration and operation to ensure a closer to the best possible working condition for prime movers. The diesel-electric and turbine–electric system has also developed rapidly since the 20th Century and is widely used in the marine industry. On a diesel-electric ship, the engine operating conditions can be adjusted by assigning the load to different engines. However, the amount of energy generated by the prime movers has a linear relationship to the total power requested by the propulsion and power demands of the vessel, and these vessels typically have about 10% to 20% energy conversion and power distribution loss. Usually, diesel-electric systems are considerably quieter than conventional direct drive propulsion system.

Combined marine propulsion is widely using in naval ships. Recent design histories of both naval and commercial vessels are characterized using combinations of different sizes of diesel engines or gas turbines to meet propulsion and electrical loads. For maritime applications, the primary concerns are the performance and the reliability, these systems combine different prime movers such as diesel engines, gas turbines or electric motors, and sometimes are called 'hybrid ship' [11], and used different fuel converters for various tasks. However, for industrial applications, life cycle cost is a significant concern.

Typically, conventional diesel-mechanical ships are considered efficient but expensive to operate. The issues with the traditional propulsion system are due to the direct connection between the engine working condition and propulsion load. The engine load is generally affected by the propulsion load, and an engine under low load operates with lower efficiency. At high speed, the engine is running at its top efficiency with an adequately matched propeller and gearbox. At the cruising speed, the engine is usually lightly loaded with reduced fuel efficiency.

The hybrid electric propulsion system can help improve efficiency at cruising speed by engine cycling or buffering the energy from the engine and returning this to the drive shaft later by the electric machine. Which this method, the engine operation is shifted to a higher efficient zone or can be turned off when applicable. Extra redundant is also added as more power source is integrated into the propulsion system.

On the other hand, with the increasing concern on the environment, global warming, and carbon footage, the industry starts to concentrate on the reduction of the environmental impact using new and advance technology. While the IMO targeting 50 percent fewer CO_2 emissions by 2050 from the 2008 level (at least 40% by 2030) [3], the industry is seeking solutions for future propulsion systems in urgent need. Inspired by the automotive industry, and with the development of the Li-ion battery industry, considerable attention has been paid to the hybrid electric maritime propulsion [12]–[14].

Overall, the hybridization of a ship propulsion system can provide:

- More redundancy
- Reduction in fuel consumption and maintaining cost
- Reduction in emission and GHG
- Zero-emission operation
- Reduction in ship-induced noise
- More flexibility to meet the growing environmental policies and legislations

A hybrid can only improve overall efficiency as long as the overall system is well designed and studied. However, not every hybrid design and control can achieve better performance on fuel economy and emission, and some can even end up being less efficient than conventional diesel or diesel-electric architecture.

1.4.1. Hybrid Propulsion System Architecture

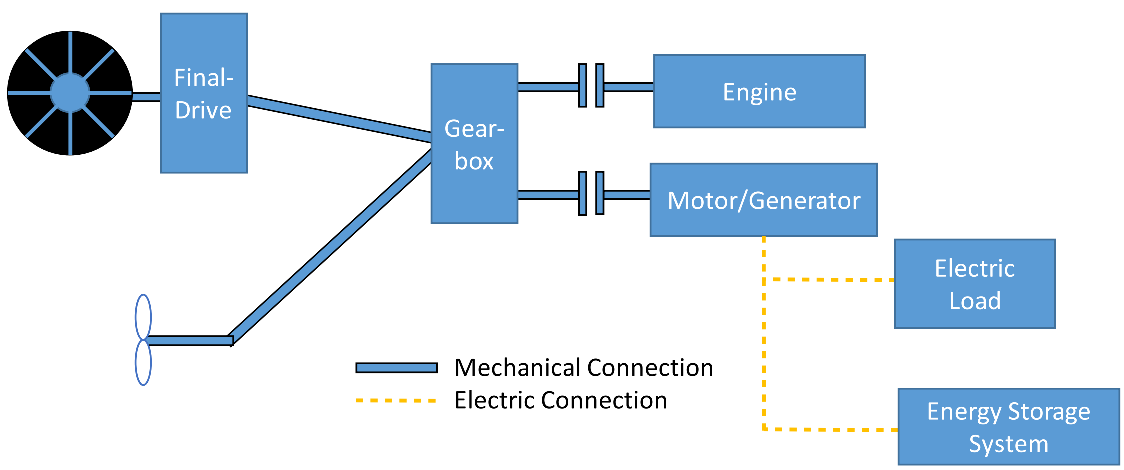

Figure 2 Inspiration from Automotive Industry

The hybrid powertrain on the land application and maritime applications share plenty of features. The architecture of the hybrid propulsion system can roughly divide into three categories, parallel, series, and series-parallel.

For series architecture, the propeller is driven by an electric machine, and the onboard generator set generates electricity and supports the propulsion and hotel load. However, there exists more efficiency loss during energy conversion at the electric machines (EMs), convectors/invertors, and ESSs. The advantage of this type of hybrid electric system is that the diesel generator set can operate at its' highest efficiency points and together with ESS, supplying the dynamic electrical load. Also, a smaller diesel generator can be chosen as increasingly embed energy sources, and larger motors are embedded into the system, in the meantime providing sufficient redundancy to the system.

As for parallel architecture, it retains the mechanical link between the main engine and propeller shaft, and the motor is connected to the propeller shaft in parallel to the main engine through some mechanism. Intrinsically, each propeller can be driven by an engine or EM or a combination of both.

By combining with architectures together, the ship can operate in different modes, and the controller (or operator) can switch from one operation mode to another freely. This design provides more degree of freedom comparing to the sole series or parallel architecture with further improved efficiency and reliability. The added complexity of this design requires more understanding and experiences in hybrid electric ship design and operation.

The ESS in the hybrid electric system operates as a buffer and store the energy temporarily, adding more degree of freedom to the engine and complicates the design and control. The capacity of the ESS is decided by operation tasks and need to be analyzed case by case. However, smaller ESS provide limited pure electric mode ability but require less investment and can be recharged by onboard diesel generators. Larger ESS is chosen for which can charge the ESS using the energy from the grid. When the ship is moored in the harbour at night, the charging facility can charge the ESS if the hybrid propulsion system can use the energy from the grid instead of only using the power from the diesel generator sets. And when the load demand is low (such as in [15] in low load sailings), the ship can be operated by the batteries feeding the electric machines.

Several different studies have been carried out[15]–[20]. However, with a different configuration, operation profile and various types of ships, the conclusion conflict with each other due to different operation profiles, and not all hybridization circumstances make sense. There is an urgent need to investigate the potential of a hybrid electric propulsion system.

1.4.2. EMS for Marine Applications

The traditional control of the ship propulsion and electric power systems is simply aimed at meeting the electric power demand using a fixed frequency generator and batteries, through the manual control by an operator or following simple operation rules programmed in the controller. A considerable amount of effort has been devoted to the design optimization of marine vessels [21]. Similarly, optimal power control and energy management strategies (EMS) should be introduced during the operation of these vessels to achieve the best energy efficiency and emission reduction.

1.5. Outline of the Thesis

This dissertation can be divided into four parts:

- Chapter 2 and Chapter 3 mainly focus on the modelling of the vessel operation profiles and the performance, emission, and power loss of key propulsion system components, as well as the modelling method. The architecture of a hybrid electric propulsion system is introduced, and the benchmark diesel-mechanical propulsion system is modelled with its performance simulations. Other propulsion architectures are also presented and discussed.
- Chapter 4 presents two different EMSs used in this study, and those EMSs are applied to the various propulsion systems introduced in Chapter 2. The obtained simulation results from two classic propulsion system designs, the conventional diesel-mechanical ship, and the diesel-electric ship, are compared. The study used the BC Ferries' MV Tachek, operated on the Quadra island - Cortes Island route, as a research platform.
- Chapter 5 focuses on solving the optimal design problem to identify the optimal sizes of the critical propulsion system components with embed controllers. A nest optimization problem is formulated, and a metamodel-based global optimization algorithm is used to solve the formed optimization problem.
- Summary and future work are presented in Chapter 6.

Chapter 2 MODELLING OF SHIP OPERATION PROFILE

The operation profile of a marine vessel is a model that represents its normal operation patterns. The profile consists of series of temple data points of travelling speed, propulsion power, electric load, GPS route, rudder angle, and some operation environment conditions, such as ocean current, wave, wind, and temperature. The operation profiles can be used as inputs to the vessels' propulsion system to assess vehicle performance, measured by ship speed, fuel consumption, emissions, and dynamic response, and to predict the life-cycle costs of the vessels' propulsion system. The operation profiles of ground vehicles usually include only driving and load cycles due to the simplicity of their operation. Due to diversified propulsion system configurations and operation tasks, a generalized operation profile for marine vessels is infeasible. However, the operating profiles of similar vessels with similar operation tasks could be identified to guide the design, analysis, and control developments for the same class of marine vessels. The identification of three categories of marine vessels, passenger and car ferries in British Columbia, port tugboats, and lobster fishing boats in marine-time Canada is one of the critical research tasks of our UVic research team and of this thesis work.

Traditionally, the design of naval architecture is carried out based upon primary ship performance and operation requirements, including contact speed, seakeeping ability, vessel operating environment, lifetime cost, etc. The marine engineering team designs the ship hull, propulsion system, electric system, etc. Advanced experimental and numerical simulation tools have been introduced to accurately predict the static drag of a ship hull and propulsion force of a propulsor. These tools include the tow-tank experiments and the soft tow-tank simulations using the computational fluid dynamics (CFD) programs. These simulations present solutions for average drag and propulsion force balance for a marine vessel under design and estimates on the vessels' power requirements, to facilitate the selection of propulsion system and determine the engine alternator ratings [21]. After evaluating and comparing various ship hull-propulsor and propulsion solutions, the "best" overall design based upon the designers' experience and judgments are selected. However, due to the complexity of various influencing factors in ship propulsion system design, the dramatic variation vessel operations, and the limits manually performed system-level calculations, many ships could not perform well under the given design conditions. These led to a less “optimal” propulsion system design with inefficient operations.

The CFD simulations can be used to generate propulsion power needs at different speeds, but these numerical simulations are computationally expensive, time-consuming, and dependent upon special computation facilities and multidisciplinary knowledge. Human interventions are needed to interpret and use the simulation results in designing the vessels’ propulsion system. Most importantly, the prediction of drug-propulsion forces and the design/simulation of the propulsion system are separated due to the intensity of the two different types of modelling and simulation work. The integrated design at the system level to optimize the propulsion system component sizes and operation controls, which may require thousands of evaluations, could not be conducted.

The first step for the integrated system design, simulation, and optimization is the accurate modelling of the vessels’ operation profile that serves as the system and design inputs. To better understand the operating conditions and load profile of a marine vessel. Two representative passenger and vehicle ferries, operated by the British Columbia Ferry Services Inc (BC Ferries), MV Skeena Queen, and MV Tachek, are chosen to carry out ship operation data acquisition (DA). The acquired data from MV Tachek are used in the propulsion system modelling and design optimization in this thesis, and the ship and its propulsion system are illustrated in Figures 3 and 4.

Figure 3 MV Tachek Approaching Dock

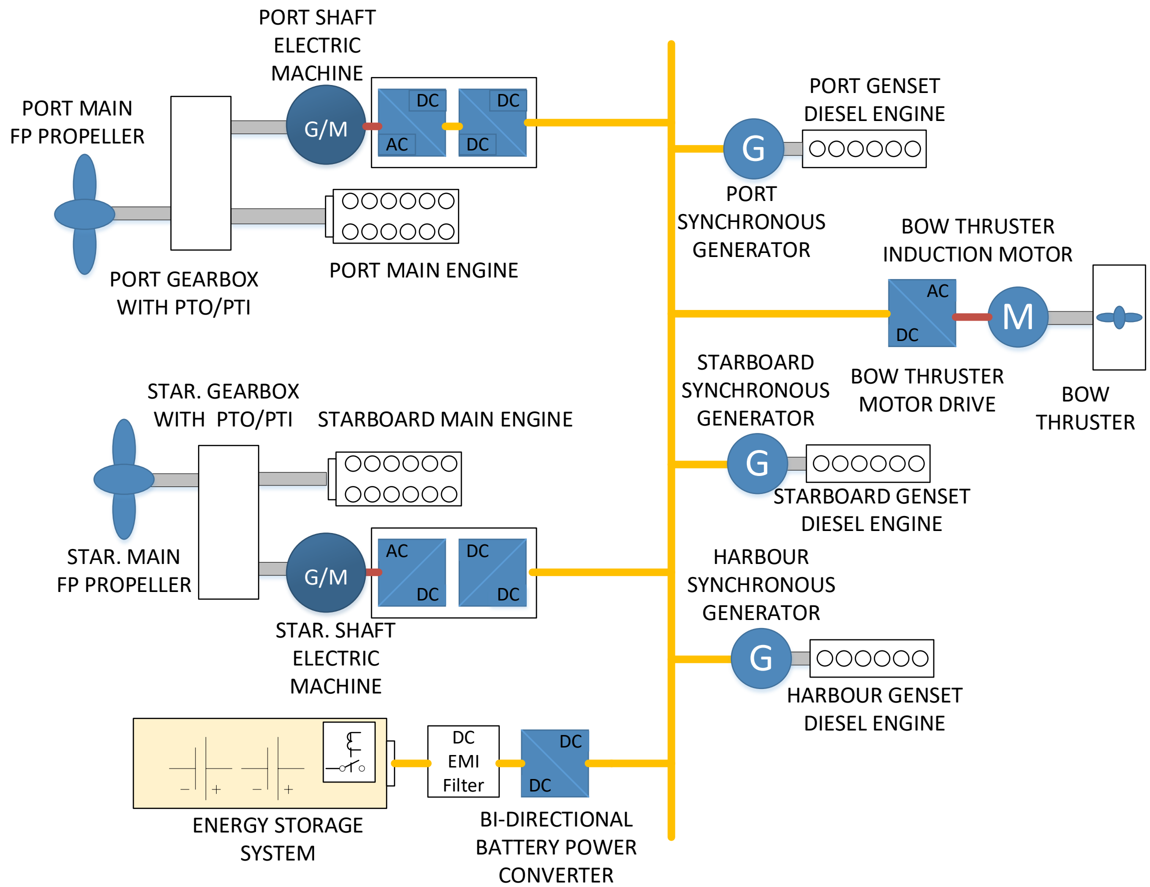

Figure 4 MV Tachek Architecture

2.1. Passenger and Car Ferry, MV Tachek of BC Ferries

The MV Tachek, operated by the BC Ferries between the Quadra Island and Cortes Island in British Columbia (BC), is one of several minor vessels in the BC Ferries fleet. In 2013, MV Tachek went through a life extension project with the addition of an innovative hybrid electric propulsion system.

Power Take Off (PTO) / Power Take In (PTI) are two different power control modes used in marine propulsion. In the traditional and commonly- used PTO mode, the power is taken off from the propulsion engine to drive the propellers and to power various pumps, compressors, generators, and other ancillaries. In the PTI mode, power is taken in from the ESS to propel the vessel in full or in part. The new hybrid electric propulsion system is capable of operating in both modes or support the PTO/PTI operations.

The original MV Tachek had a diesel-mechanical drive initially. The hybridization made to the powertrain system in 2013 was conservative, turning it to a PTO hybrid electric ship with the following two major changes [22].

1) Two larger diesel engines (985 kW each) with a 45% power increase replaced the old engines (640 kW each). The change was made to address the engine overheating issue of the ferry under some extreme operating conditions, and to support the new PTO operation; and
2) Upgrade of the vessel's propulsion system to a PTO hybrid ship was done to allow the engines-generators and the battery ESS to replace the old gensets to supply hotel loads and to drive the tunnel thruster of the vessel during docking operations.

2.1.1. Vessel Description

The MV Tachek has been retrofitted with a hybrid electric system with an added onboard battery ESS to assist the ferry in docking and departing. The ship equips with two variable speed generators driven through PTO from each gearbox, driven by the main engines. Usually, the diesel generators for ship power supply no longer need to operate. The Li-ion battery ESS connects to the electric bus through a bi-direction DC/AC converter and supplements the PTO generators to meet peak power demand when the bow thruster operates during ship docking and departure. The system charges the ESS during cruising when less power is needed [22], [23]. Since the shaft generators had no propulsion function, the part-time hybrid electric propulsion system had not realized the full potential of the hybrid electric propulsion system.

2.1.2. Present Propulsion System

The specifications of the ship are presented in Table 1. The shaft generator is connected to engine shaft through a PTO gearbox, the gear ratio between the shaft generator and the engine is 1:1. During sailing, the engines operate at a slightly higher load than the prolusion power need, charging the ESS and supplying the hotel load. The ESS stores the energy for driving the bow thruster later during docking. The onboard diesel generators often operate in standby mode and never kicks in unless needed by an emergency operation.

Table 1 MV Tachek Characteristics [22]

Built	1969, Vancouver (Refit in 2013)
Overall Length	49.53 metres (162'6")
Maximum Displacement	807 tonnes
Car Capacity	26 Automobile Equivalent (AEQ)
Passenger & Crew Capacity	150
Diesel Engine	940 kW × 2
Gearbox Ratio	4.63:1
Shaft Generator	160 kW (MAX) and 69 kW (CONT.) × 2
PTO Gearbox Ratio	1:1
Diesel Generator	99 kW × 2
ESS	114 kWh (LiFePO4 batteries)
Maximum Speed	12.5 knots
Amenities	None
Route	Quadra Island (Heriot Bay) - Cortes Island (Whaletown)

2.1.3. Unique Feature of the Ferry and Its Operations

MV Tachek is an ideal ship for hybrid propulsion studies for several reasons. MV Tachek operates in open water with varying marine weather conditions, resulting in a significant change in the ship operation and engine load. Secondly, the ship is a modernized with an alarm monitoring system using Modbus TCP/IP to allow the ship's control system developer, TECHSOL, to monitor the ship operation remotely. Using this set-up a customized data acquisition program plugged into the onboard Ethernet local area network (LAN), was developed by our research team to record ship operation data. Finally, as the first hybrid PTO electric ship with Li-ion battery as ESS, the vessel is ideal for evaluating the efficiency improvement of a hybrid electric propulsion system.

2.1.4. Goals of Research Related to Tachek

Studies on the Tachek will produce a better understanding of its operation pattern and explore the potentials of adopting new hybrid electric propulsion system designs and optimal controls. Besides, the ferry operates in open water with varying marine weather conditions, and the acquired operation data will support future research on sailing route optimization and semi-autonomous sailing to reduce fuel consumption, emissions, and ship-induced noise [22].

2.2. Acquired Ship Operation Data and Their Usage

The modelling and operation simulations of the hybrid electric propulsion system are carried out under certain ship operation conditions and time-relevant operation profiles for analyses on fuel consumption, degree of hybridization, control and energy management strategies. Due to the complex operation standard, rules, regulations and different environmental conditions for different operators and ship owners, standard ferry operation profiles are not available. To understand the ship operation the operation profile data, including ship speed, heading, wind speed, wind direction, shaft speed, shaft power, engine speed, rudder angle, GPS coordination, and electric usage, are collected during ship operations with the assistances from BC Ferries and other collaborators.

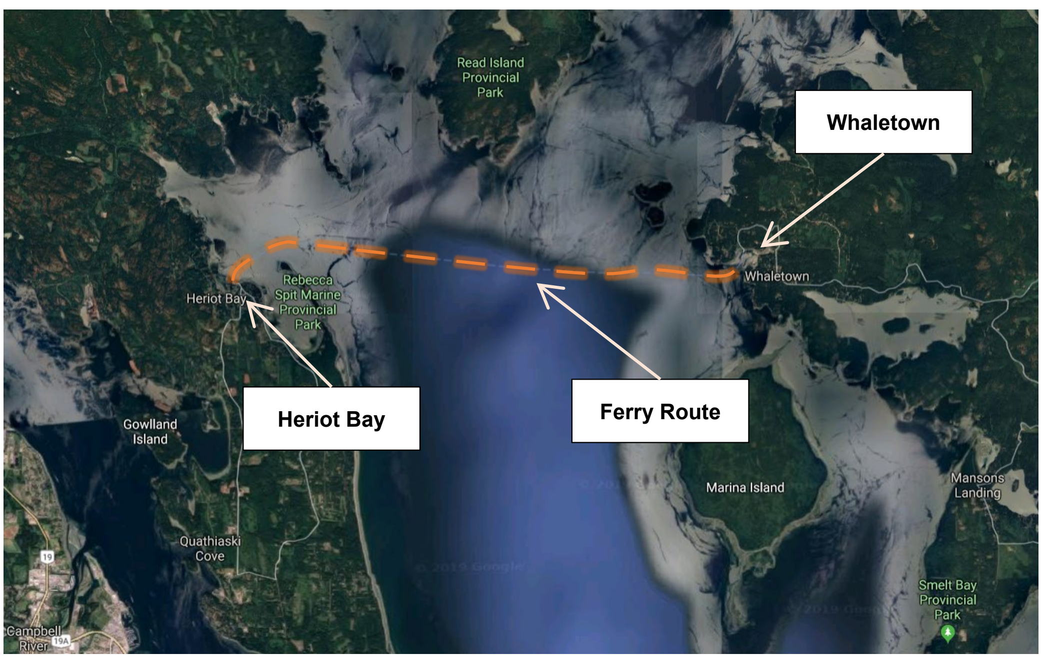

Figure 5 MV Tachek Route

The data acquisition project collected all information and data that affect the ship propulsion, including main engine power and speed, and wind speed. Electric loads were also measured to investigate electrical energy consumption and power flow in the electric system. Ship operation data, such as rudder angle, propeller speed, and ship heading, were also collected. Furthermore, the GPS information provided ship operation trajectory and ship speed were also acquired for validating the modelling results and for future study.

The operation profile collection and modelling process can be divided into three different sub-blocks for the ease of modularization

1) Propulsion power and ship operation conditions
2) Service power
3) Environmental conditions

The propulsion power and system operation conditions represent the primary system power demand during the operation of the ship. These are critical for estimating ship fuel consumption. The shipboard electric power for onboard services is generated by the alternator and prime mover working jointly, supporting the ship's steering gear system, a navigation system, communication and alarm system, as well as heating and cabin lighting. The ship operation environmental conditions include the seasonal wave, ocean currents, and wind direction and speed. The added resistance from these additional sources plays a vital role in propulsion power estimation.

2.3. Modelling of Propulsion Demands during Routine Operations

The propulsion power on MV Tachek is from two 940kW diesel. Tachek also equipped with fixed pitch propellers and rudder systems. The operation profile model provides:

1) Engine power and speed
2) Other ship essential operation conditions, such as heading, latitude and longitude, thruster speed, rudder/azimuth-pad angle, ship speed, etc.

2.3.1. Engine Power and Engine Speed

Engine power is measured using a wireless data acquisition system using strain gauge shaft torque and rotation speed sensors, which was produced by BeeData. This system sends measured data wirelessly to a receiver and a computer that processes and stores all acquired information [24]. Two sets of strain gauges were installed on the two propeller shafts of the Tachek. A snapshot of the acquired propulsion power and speed data from Tachek is shown in Figure 7, after applying a low pass filter and mean value filter to remove the noises of the raw data. The measured engine speed was verified, using the recorded data form Tachsol's built-in alarm monitor system through a customized data acquisition software developed by Michael Grant of our research team.

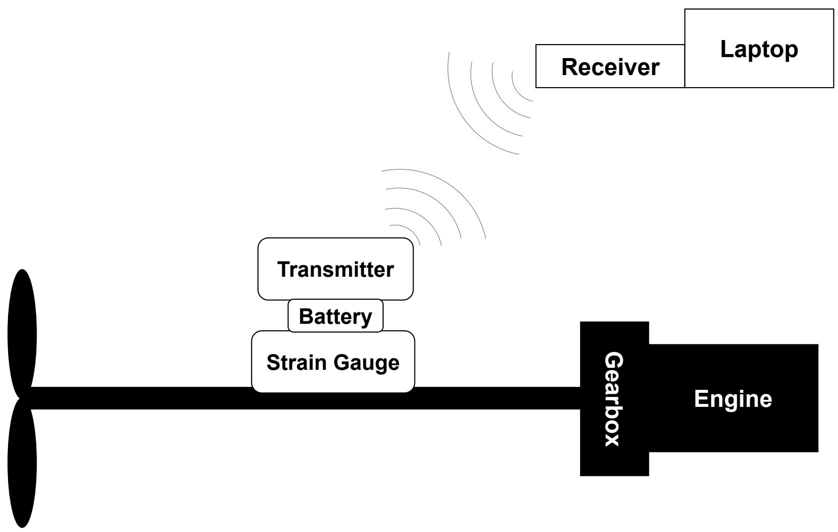

Figure 6 BeeData Wireless Strain Gauge Operation Diagram

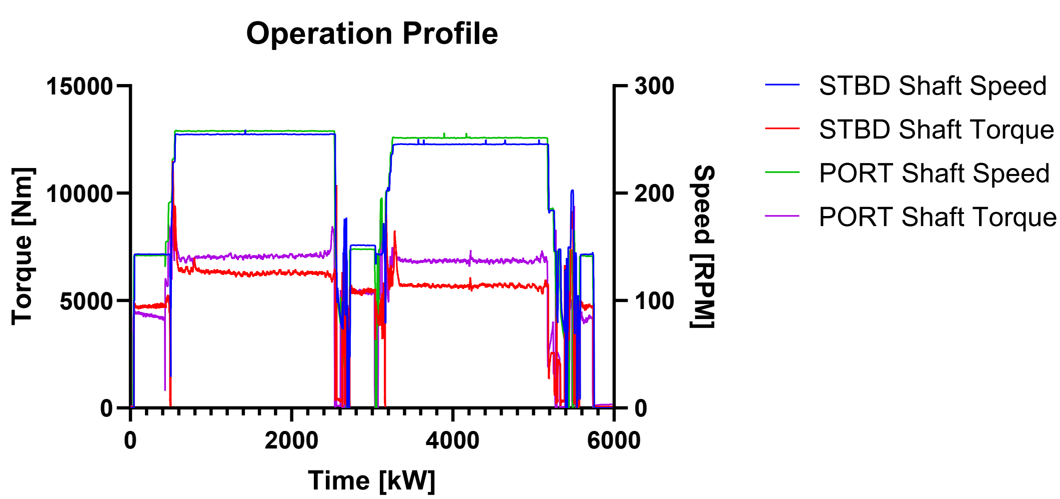

Figure 7 PORT and STBD Shaft Operation Profile

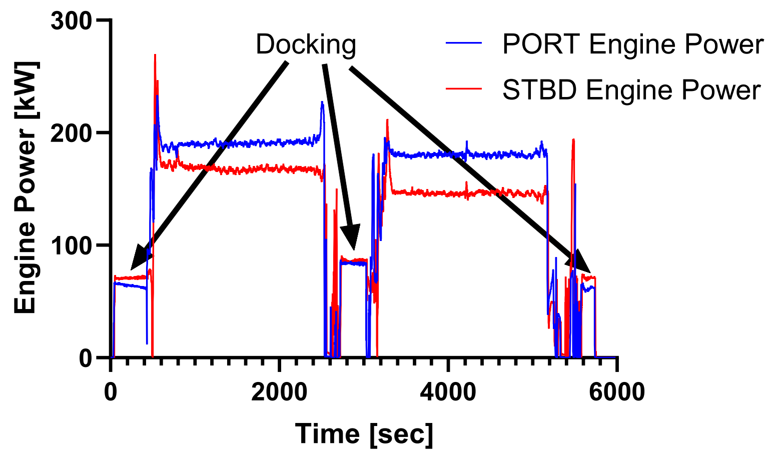

Figure 8 Engine load on MV Tachek

2.3.2. Rudder Angle, Propeller Speed, and Ship Speed

All BC Ferries vessels are equipped with voyage data recorders (VDR) to record useful information for ferry operation analysis. These recorded data are not enough for modelling and design optimization of the hybrid propulsion system. Available data is not the same for different ships, and all raw data are decoded and processed. Available data for Tachek include the following.

Table 2 Tachek Operation Propulsion Data

Available Data	Format
Rudder Angle:	NMEA 0183
Engine Speed:	NMEA 0183 / Modbus TCP/IP
Heading:	NMEA 0183
Propeller Speed:	NMEA 0183
GPS:	NMEA 0183
Bow Thruster Motor Power:	Modbus TCP/IP

2.4. Modelling of Service Power

During the 2013 refit, a Techsol data monitoring and alarm system that uses the Modbus TCP/IP has been installed. A customized data acquisition program was developed by a member of our research team, Michael Grant, to retrieve and store data in the system, including the electric load of the ship, as presented in Figure 9.

Table 3 Tachek Data Regarding Service Load

Available Data	Format
Shaft Generator Power:	Modbus TCP/IP
Bow Thruster Motor:	Modbus TCP/IP
DCDC Converter Power:	Modbus TCP/IP
ESS Power/Current:	Modbus TCP/IP

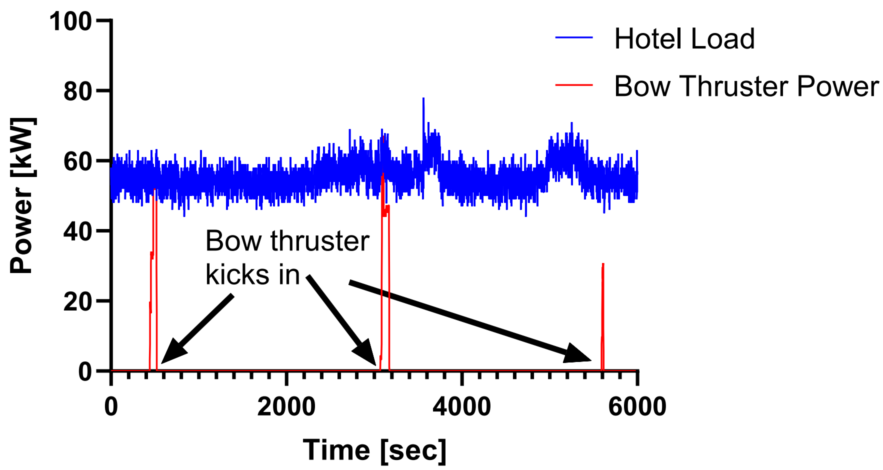

Figure 9 Electric Load (unprocessed) on MV.Tachek

The ship has been refitted with a hybrid electric drive system with an added onboard li-ion battery to assist the ferry in docking and departing. Two shaft generators generate electricity and perform as primary electric power sources during sailing. Shaft generators are monitored by the Techsol alarm system, and the vessel operation data are collected by the UVic Modbus TCP/IP data acquisition system.

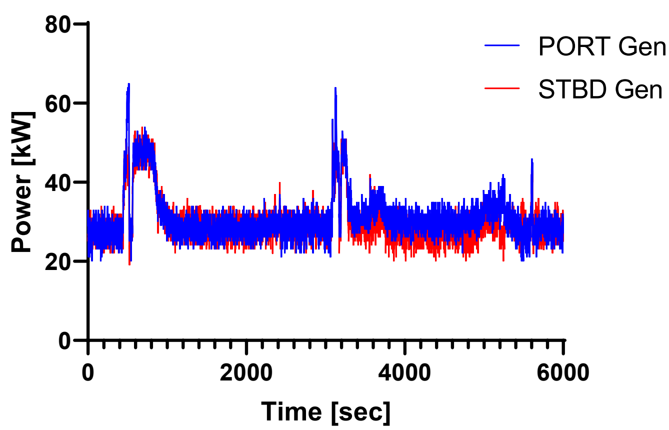

Figure 10 Shaft generator power (unprocessed) on MV.Tachek

The electric load on M.V Tachek is also recorded. A 110 kW AC induction motor driven bow thruster to make the ship more maneuverable is used to push the vessel to the dock at the wharf, and push the ship away while leaving. Figure 9 shows the recorded fluctuant electric loads due to the bow thruster operations for vessel docking maneuvering. The ESS and generator power the electric machine of the bow thruster separately or jointly following the controller's commands. As a PTO hybrid ship, the ESS and shaft generators could provide the electrical power simultaneously.

Furthermore, onboard diesel generators can kick in and provide electricity if needed. The bow thruster only operates a short period during the crossing. The electric energy produced by the generators thus does not reflect the actual amount of electrical power consumption and the ESS operates as an energy buffer to store the electric energy temporarily. The fluctuation of electric power demands thus needs to be monitored.

2.5. Marine Weather Conditions

On MV Tachek, the VDR records the ship's operation and stores the results onto a file for later analyses.

Table 4 Tachek Data Regards to Environmental Condition

Available Data	Format
Wind Speed:	NMEA 0183

Chapter 3 MODELLING HYBRID SHIP PROPULSION SYSTEM

In this chapter, the modelling platform is introduced. The proposed propulsion system is modelled in the Matlab/Simulink environment, and the overall system modelling diagram is presented.

3.1. Objective

Goals of this section are:

a) Illustrating the architectures of hybrid propulsion systems
b) Developing modular models of propulsion components for ease of use.
c) Identifying the critical features and possible propulsion system designs of a hybrid propulsion vessel.

In developing the generic passenger vessel, the main design objective is the low lifetime cost while satisfying the regulations and meeting the performance requirement. The lifetime cost varies and is a broader topic. Thus it is not discussed in this work, but only the fuel consumption is taken into consideration.

Following model-based design (MBD), this model platform includes diesel engines, diesel generators, electric machines (EM), double input reduction gearboxes, the ESS, electric load block, etc. This backwards-facing simulator calculates the power flow backward, from the propeller shaft to the gearbox, to the electric machines and engines. The fuel consumption, electrical energy, and power loss are calculated according to the pre-defined fuel/efficiency map. The specific components information is obtained from steady-state experiments and can be used to predict the performance and fuel consumption (or energy losses).

3.2. Modelling of Key Powertrain System Components

This section illustrates all the necessary modules in the modelling platform.

3.2.1. Engine Model

An internal combustion engine (ICE) can be modelled mathematically based upon the multiphysics principle or used empirical data. In industrial practices, the latter is widely used due to its simple form and relatively high accuracy. The engine models normally capture power performance characteristics, fuel efficiency, and various emissions of the engine under different operation conditions. The performance characteristics of the engine capture its peak power and torque, as well as the capability to respond to the power demand quickly. The engine's fuel efficiency under different operation speeds and torque outputs are normally measured using the Brake-specific fuel consumption (BSFC) that records the amount of fuel the engine used to produce shaft power. It is represented by the fuel consumption rate in grams per second (g/s) over the power produced in watts (or horsepower). This power is calculated by the product of engine speed and engine torque ($P = \tau\ \omega$). The engine's BSFC model is formed from the engine operation data acquired from the engine dynamometer experiments. The amount of fuel consumed at different engine speed and torque is fitted to form a fuel efficiency map of the engine using engine speed and torque as two control variables, and with the maximum engine power marked as an operation constraint curve. An example engine BSFC map is shown later in Figure 11.

The BSFC map shows the ideal engine operation zone with high fuel efficiency, indicates how a specific engine operates in actual use by plotting its operating points on the map and supports the calculation on the amount of fuel needed for the propulsion. The BSFC model of the engine, in the unit of gram/s per kilowatt, or gram per kilowatt-hours, is then calculated at each point and the continuous contours of the map are formed by interpolating the BSFC data. The fuel efficiency and fuel consumption cost calculation for a vehicle over a specific trip are based on the engine operating points on this BSFC plot. Similarly, various engine emissions, including CO_2, CO, HC, SO_x, and NO_x, are also obtained empirically and modelled using different emission maps under different engine speed and output torque. Forming these engine fuel efficiency and emission map involves a huge amount of time and effort. The models used in this research were from the US-DOE National labs and the automotive manufacturers.

Tachek is equipped with high-speed marine engines from Mitsubishi, which have high rated power and high operation speed. Due to a lack of BSFC data and models for this heavy-duty engine, the model from a similar diesel engine, the Caterpillar 3126E, which shares the same technology with lower-rated power, is scaled up to using the specifications of the Mitsubishi engine. Model scaling is a commonly used practice in forming powertrain system models. Figure 11 shows the 940kW scaled diesel engine's BSFC map and the corresponding maximum power limits. Figure 12, Figure 13 and Figure 14 show the engine emission maps.

These models are critical as they represent the engine efficiency, fuel rate, and the number of air pollutions that engine produces at the corresponding operating speed and torque output. The engine efficiency at different speed and torque can be calculated by:

$$\eta\ (\omega\ ,\tau)\ = \frac{3600000}{C_{BSFC} \times LHV} \tag{2-1}$$

where ω and τ are the engine speed (rad/s) and torque (Nm) respectively, *LHV* is the lower heating value of the fuel in the unit of joule per gram, C_{BSFC} , in the unit of gram per kWh, is the corresponding number at selected ω and τ on the BSFC map. And the fuel rate $\dot{m_{fuel}}$, in the unit of gram per second, at each operation point can be calculated by:

$$\dot{m_{fuel}}(\omega\ ,\tau)\ = C_{BSFC} \div 3600000 \times \omega \times \tau$$

The emission, $\dot{m_{emis}}$, in the unit of gram per second, can be deduced by:

$$\dot{m_{emis}}(\omega\ ,\tau) = C_{emis} \div 3600000 \times \omega \times \tau$$

where C_{emis} is the corresponding number at corresponding ω and τ on each emission map.

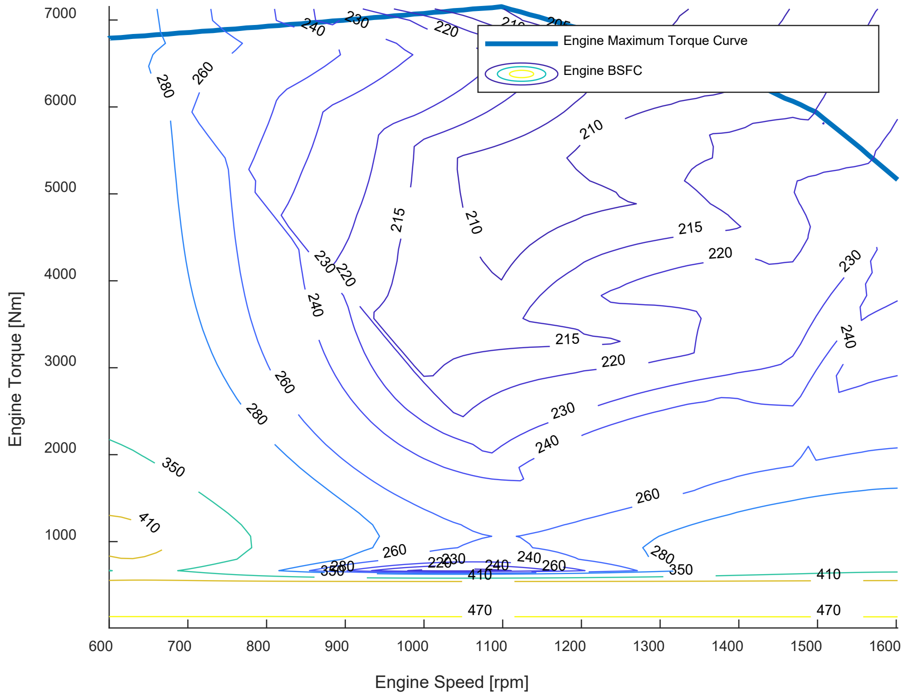

Figure 11 Engine BSFC map with maximum available torque

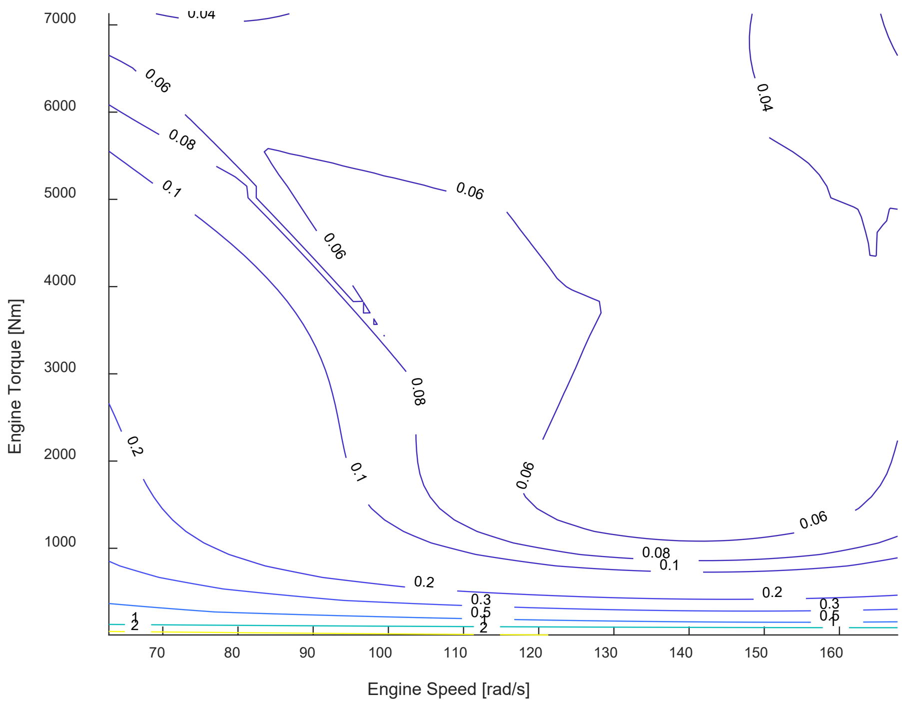

Figure 12 Engine HC map

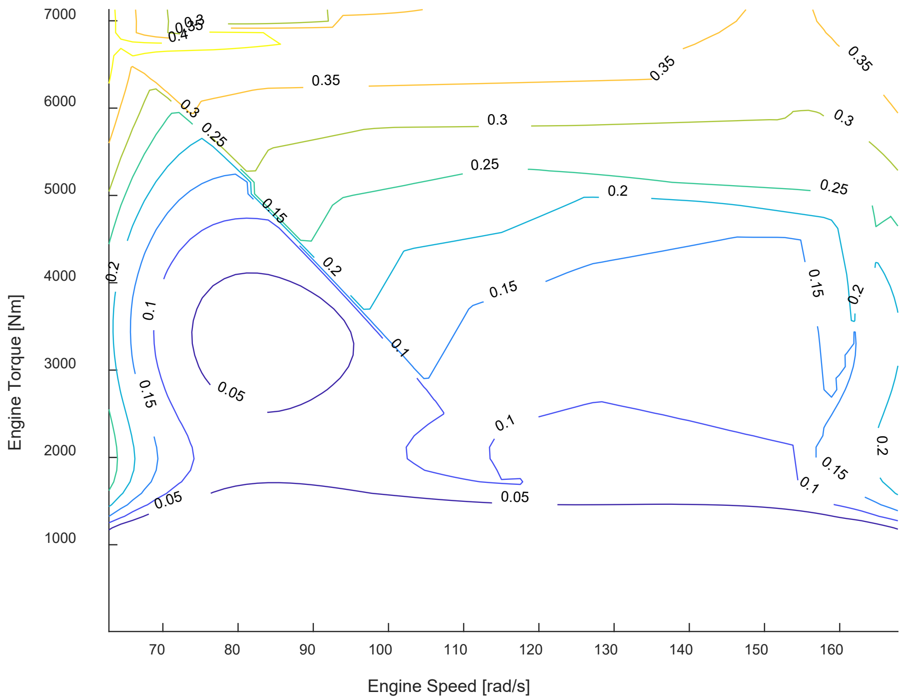

Figure 13 Engine CO emission map

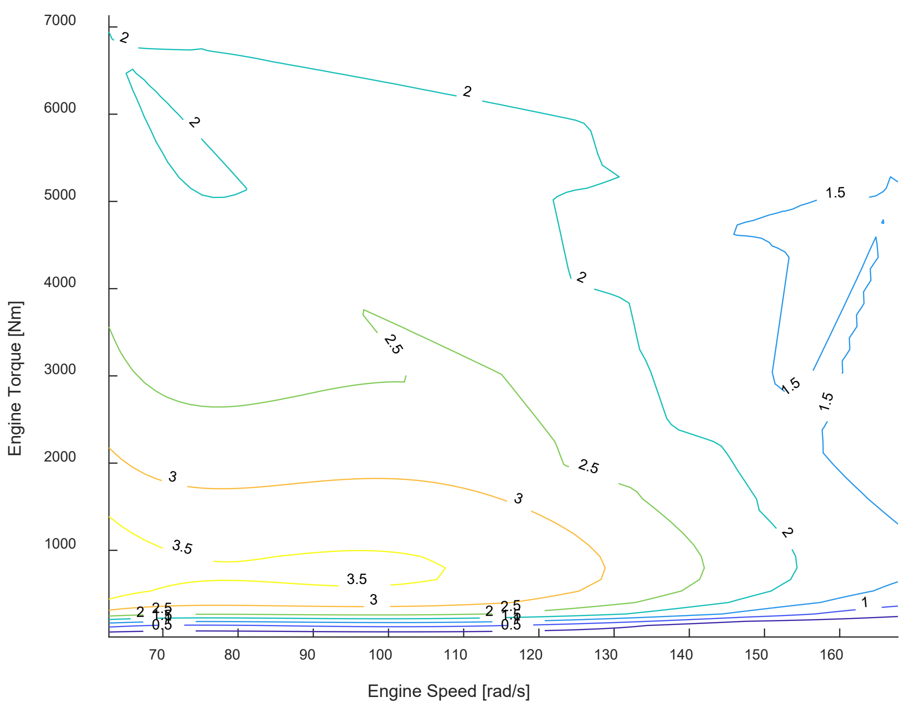

Figure 14 Engine NO_X emission map

The engine model used in this study is based on the Caterpillar 3126E engine tested by the National Renewable Energy Laboratory (NREL) [25], [26]. The original engine is tested at Battelle over European Stationary Cycle, and Dr. Yanbiao Feng scales the engine to meet the high-speed heavy-duty engine performance characteristics as used in this study. The engine validation result is presented in Table 5 and is proved to be accurate. Those validations represent the error between tested engine and the experiment data.

Table 5 Caterpillar 3126E Engine Validation [26]

Item	Average Error	Maximum Error	Max error at speed (RPM)	Max Error at Torque (Nm)
Fuel	0.24818%	0.67731%	2200	890
CO	2.5402%	19.1852%	1440.2	263.8042
HC	0.6856%	-2.7346%	2200	890
NOx	0.76643%	3.9308%	1440.2	263.8042

Table 6 compares the scaled engine to the installed engine's fuel rate curve from the manufacturer's datasheet. The result shows that the scaled brake specific fuel consumption of the engine is accurate enough for a relative comparison. The scaled emission data is used due to the lack of actual engine emission data.

Table 6 BSFC Error Comparison at Different Load and Different Speed

Speed (RPM):	1008	1170	1270	1454	1600
Torque (Nm):	4196	1995	3701	4849	5895
Scaled Engine (g/kWh):	212.9	244.8	218.8	218.8	219.9
S60 (g/kWh):	207	223	209	213	224
Error:	2.85%	9.78%	4.69%	2.72%	1.83%

The engine is modelled using the static experimental data such as engine speed limits, maximum and minimum torque, and brake specified fuel consumption map in the form of lookup tables, which calculate the engine efficiency and fuel consumption. The emission model receives the engine operating speed and torque, then calculates the corresponding emissions based on experimental data.

The transient response of the engine is relatively fast for the simulation sampling interval and can be neglected. Thus, it is represented using a first-order transfer function.

3.2.2. Electric Machine Model

Similar to engine modelling, heavy-duty electric machine experimental efficiency data is not available. A smaller AC motor is scaled up to meet the rated power. The thermal effect is taken into consideration as the motor core temperature increases significantly when actions such as motor brake and overload occur. The EM and electric drive combined efficiency is shown in Figure 15.

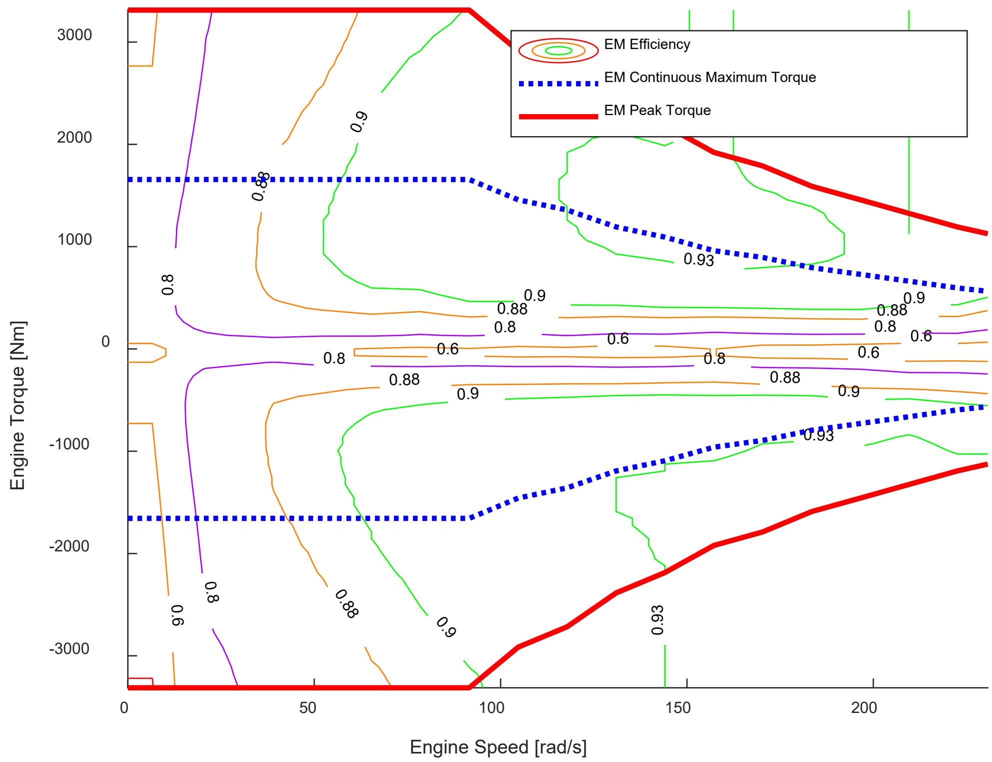

Figure 15 Electric machine combined efficiency map

Same as engine dynamics, the dynamic behaviour of the electric machine is relatively fast for the sampling interval and can be neglected. Therefore, this dynamic is represented using a first-order transfer function.

3.2.3. Gearbox Model and Shaft Power Losses

As the ship is equipped with high-speed marine diesel engines, reduction gear sets are needed to reduce the output speed to the designed propeller operation range. Typically, gearboxes in a boat are simply reduction gear sets and only have one gear ratio. The gearbox is driven by hydraulic pumps, whose power consumption is taken into consideration in electric load, and only mechanical losses need to be calculated. When there is no engagement among the gear sets, the engine will operate at idle speed, and consumes less fuel and can respond to orders swiftly.

The installed gearbox has a ratio of 4.63:1, as this reduces the engine operating speed to a slower optimal propeller operation speed. The mechanical efficiency is relatively high in design conditions. In general, a single state gearbox has 1~2% power loss, and the gearbox has a higher efficiency under heavy load than a partial loaded. A lookup table is usually used to calculate the power loss of the gearbox at different speed and torque.

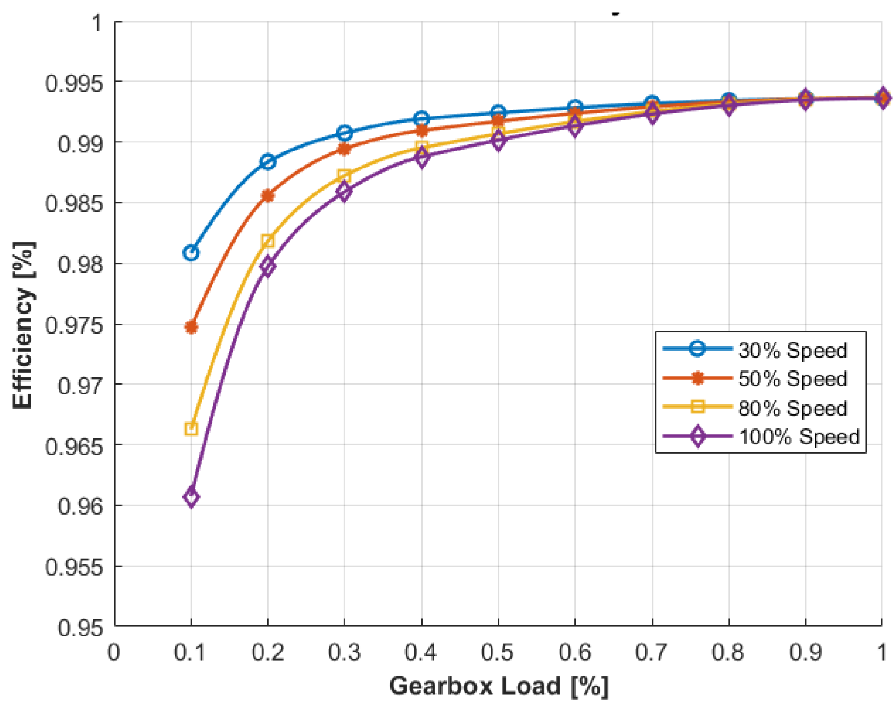

Figure 16 Gearbox Efficiency

The prime mover, propeller and gearbox are connected through the shaft, and it transfers the power through the propulsion system. Typically, only the friction would lead to power loss. In this study, the efficiency of the shaft is set as a constant: 99.5%.

3.2.4. Die-Generator Sets

A diesel generator can be simplified as a generator coupled to a diesel engine. In this application, a 180kW diesel engine is modelled using the same method and data source as in Section 3.2.1 and is attached to an electric machine. The fuel consumption is calculated backward from the needed electrical power at the propulsion motor to the electrical power produced by the generator, to the mechanical power from the engine that drives the generator. The power conversion losses have been added. Next, the fuel consumption and emissions at the corresponding engine speed and torque are deduced.

3.2.5. Energy Storage System

A hybrid electric propulsion system may use different types of electric ESS. In this work, a Li-ion battery pack, built using the battery modules from A123 and utilized in the UVic EcoCAR2 PHEV development is modelled and used. The lithium-ion (Li-on) battery has many advantages, including higher energy density, lighter weight, and longer operation life, becoming the dominant type of batteries for electric ESS in vehicular and marine applications. Several packs of the Li-ion batteries are connected in parallel and series to form a larger ESS to meet the energy storage capacity of the heavy-duty marine use, and the size and capability of each of these packs are listed in the following.

Table 8 A123 Battery Pack Characteristic

Nominal capacity (kWh)	2.46
Nominal voltage (V)	49.5
Maximum Power (Charge and discharge)	151kW peak and 51kW continuous
Battery Cells	15 in series and 3 in parallel

Typically, there are three different types of battery performance models, the equivalent circuit model [27], the electrochemical model [28], [29], and the electrochemical impedance model [30]. The most commonly used modelling method, the equivalent circuit model, presents the power performance of the battery using an equivalent circuit of capacitors and resistors to form a unit with an ideal voltage source, ideal resistors, and ideal capacitors. The electrochemical impedance models are similar to the equivalent circuit models, but the more complex model supports the measurement of system response in any operating points directly. In contrast, the equivalent circuit models typically measure the step response for several fixed operation points; the electrochemical impedance models thus provide more substantial meaning and more accurate parameters than the equivalent circuit model. As for the electrochemical models, it goes further and simulates the chemical reactions in the cell. Not only are the electrochemical models accurate for reflecting the battery dynamic and implementing optimal battery management and control studies, but they are also capable of applying optimal battery designs. However, this type of model is relatively computational expensive and requires a thorough knowledge of thermodynamic, electrochemistry and other correlation disciplines, and is overqualified for a system-level optimal design problem as in this work.

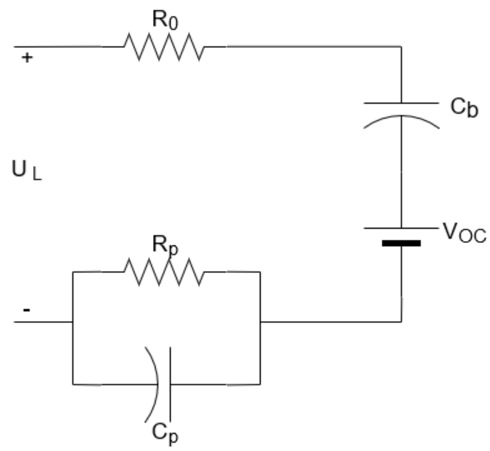

Figure 17 PNGV Equivalent Circuit Model

In this study, the PNGV battery cell model is selected to simulate the dynamic behaviours of a battery. As shown in Figure 17, C_p is the polarized capacitance, R_p is the polarized resistance, V_{OC} is the open-circuit voltage, C_b is the capacitance, R_o is the ohmic resistance, U_L is the measured battery voltage. Each battery pack consists of multi-cells and is connected in series and parallel. The battery back receives the power request from the electric bus, then divides the power and current by the number of cells according to the configuration (in series or parallel), which deduces the current in each cell. Next, the pre-defined parameters are retrieved in the look-up tables, and then the open circulate voltage and internal resistances are obtained at a different load and state of charge (SOC). The battery temperature is assumed to be constant during the ship operations for two reasons: first, the seawater temperature is relatively low and can be used to cool down the battery; second, in on-land vehicle applications, the limited spacing restricts the cooling performance. However, extra space is available under the dock in marine applications. Thus, it is possible to install cooling devices, such as active cooling equipment for ESS.

In general, there are many conventional methods to estimate the battery state of charge: open circuit voltage estimation, current integration method [27], [31], observer methods (Kalman filter, sliding mode observer, etc.) [32], [33], data-driven methods (artificial neural network [34]), etc. The current integration method is a conventional algorithm for evaluating the battery state of charge, and the accuracy proves to be qualified with carefully calibrated parameters. It can be implemented easily with low computational complexity [27]. In this study, the SOC is estimated using the integration of the charging and discharging current to calculate the SOC in the batteries, as follows:

$$SOC(k) = SOC_{init} - \frac{1}{C_n}\int_0^k \eta \cdot I(t)dt \qquad (3\text{-}1)$$

where SOC_{init} is the battery initial SOC, $I(t)$ is the cell current at time t, C_n is the nominal capacity of the battery, η presents the Coulombic efficiency. It should be noticed that the biggest advantage of the current integration method is that it simplifies the computational complexity while providing an accurate SOC estimation. However, unclear initial SOC, self-discharging, battery ageing, and sensor drifting have a significant influence on the accuracy of SOC estimation. Hence BMSs need to be calibrated frequently in real-life applications [33].

3.2.6. Hotel Load and Electric Bus

The hotel load represents the electricity that supports the onboard service except for propulsion, such as lighting, heating, communication, etc. This power demand module captures the electric power request during the operation.

As all the electric components are isolated using the invertor/convertor, the bus voltage is stable and is assumed to be a constant 750V DC. The power request from all the consumers are obtained from real-life operations and are presented in Figure 9.

3.3. Propulsion System Models

As introduced in Chapter 1, a different combination of fuel converters and electric machines are possible for hybrid propulsion systems. This study will illuminate the POT/PTI hybrid propulsion system and investigates the energy management strategies.

The model of the propulsion system of MV Tachek is introduced in this section. A conventional diesel direct drive ship equipped with a tunnel bow thruster is modelled and is used as the benchmark. The obtained simulation results are compared to the PTO hybrid electric MV Tachek and the newly proposed hybrid electric vessel. Fuel consumption is used to compare the energy efficiency of these vessels.

Based on the components introduced above, a backward-facing powertrain system simulator, which collaborates with operation profile model, the model receives the thruster power and then calculate the power demand backward, from shaft to gearbox, to the engine and EM, then to the ESS, is simulated in Matlab/Simulink environment.

The conventional diesel-mechanical (MECH) ship is modelled as the baseline for this study since this type of ship uses a typical configuration and has been widely used in the industry. This MECH ship has two prime movers, connected to the thruster through reduction gearboxes. Rudders steer the boat and control the course. Onboard diesel-generators generate electricity, supplying hotel load, and driving the bow thruster. The bow thruster, driven by an electric machine, is installed to improve the maneuverability.

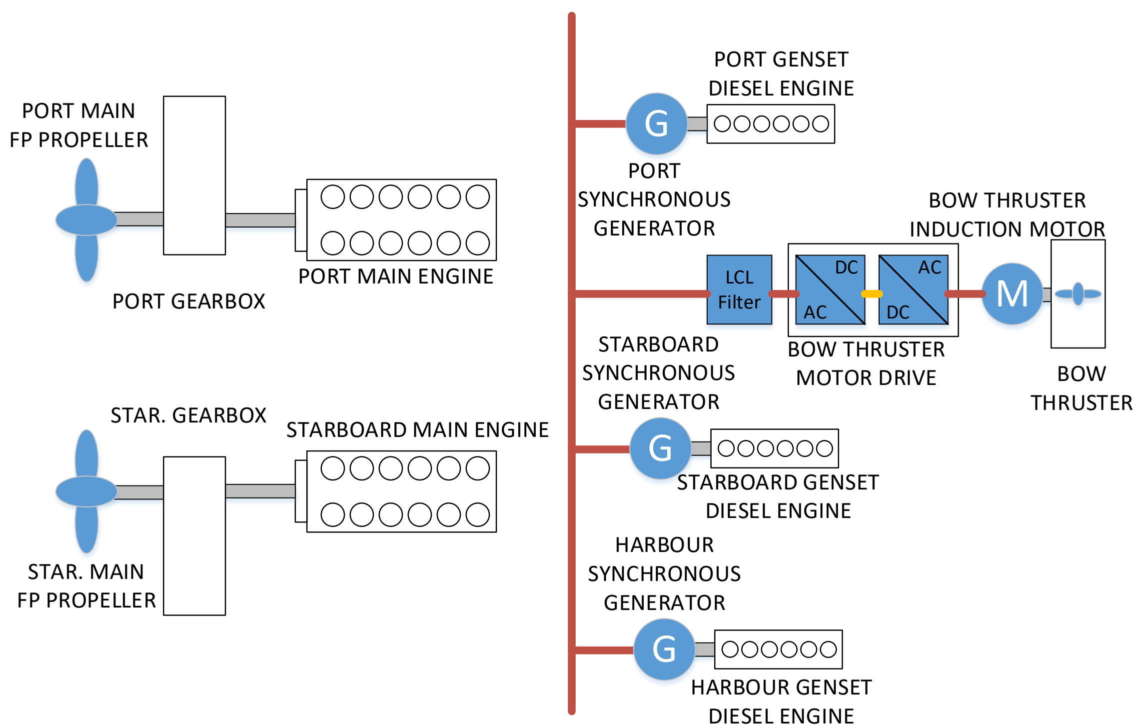

Figure 18 Conventional Architecture Equipped with Tunnel Thruster

Similar to diesel direct drive ships, the architecture of diesel-electric vessels is relatively simple compared to hybrid architecture: there exists a linear relationship between the propulsion power and the power from the power source. Two propellers are connected to the electric machines through a reduction gearbox instead of a fuel converter as in conventional architecture. An electrical link connects the electric motor and electric power source, and the onboard diesel generators generate electricity. The architecture of the diesel-electric ship is presented below:

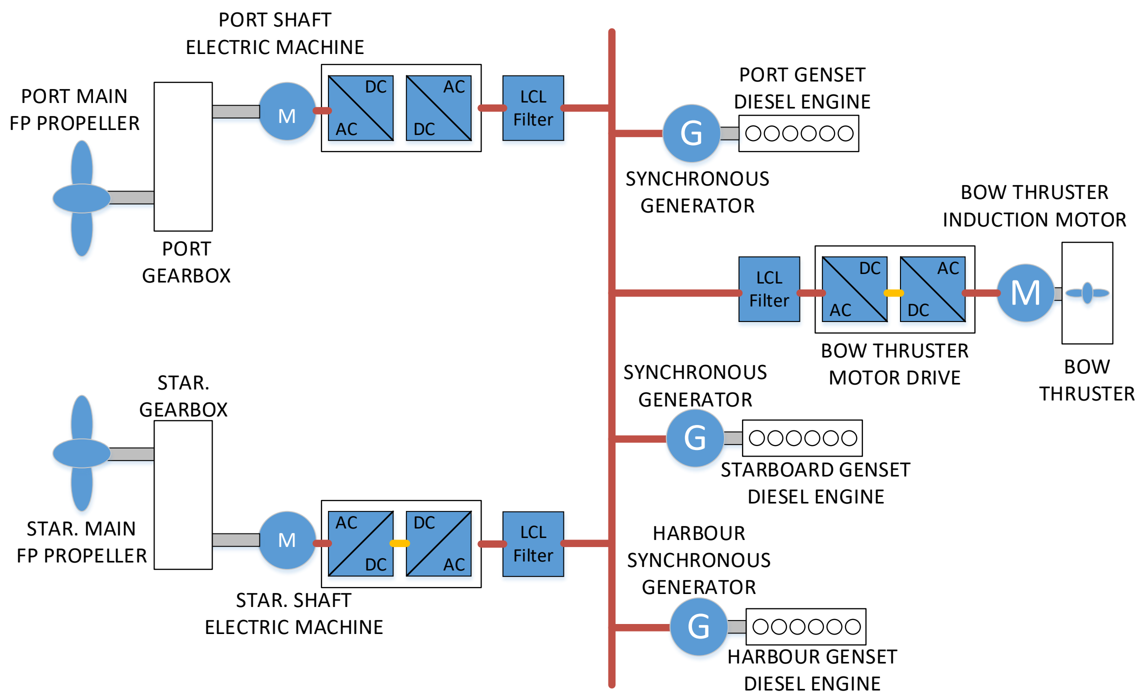

Figure 19 Diesel Electric Propulsion System Diagram

Some ships operate with Power Take Off (PTO), and Power Take In (PTI) modes when equipped with both mechanical and electric drives, as shown in Figure 20. The main engines are used to provide propulsion power through mechanical links and gear reductions to the propellers. In contrast, the gensets are used to supply auxiliary electric power to the vessel. The main engines and the gensets for auxiliary electric power often share the same power bus using different converters.

In PTI mode, instead of taking power from the main engines, the electric machine injects propulsion energy to the gearbox. When power demand is high, the engine and electric motor can provide propulsion power simultaneously. When the propulsion load is low and does not need the main engine, the electric motor can provide the propulsion power solely, the ESS, diesel-generator, and shaft-generator on another shaft line can generate the energy needed for both the propulsion and for the ship's consumers. It is also capable of start operating in the events of failure in the main diesel engine.

In the PTO mode, the gensets for auxiliary power are stopped, and the electrical power is supplied by the main engine through the shaft generator. In the PTI mode, the main engines-generators provide additional electric power (possibly through a variable-frequency drive (VFD)) to supplement the electrical power produced by the gensets. The engine is coupled with an on-off system. When the ship is propelled by the electric machines, the engine shafts will disengage from the gearbox and the main engines will be completely turned off to save fuel and reduce emissions.

An electric motor that drives the bow thruster is presented in this model as a consumer onboard. Two diesel generator sets can provide extra electric power when needed. The ESS will operate as a buffer and store the energy temporarily. The ESS can also use the energy from the grid when the charging facility is available. The hybrid architecture diagram can be simplified as in Figure 21, the engine and motor are coupling at the gearbox and can disconnect from the driveline by disengage the clutch. The electric bus distributed electric power in the system. The diesel generator, EM, and the ESS can supply the electricity to maintain the power balance of the system.

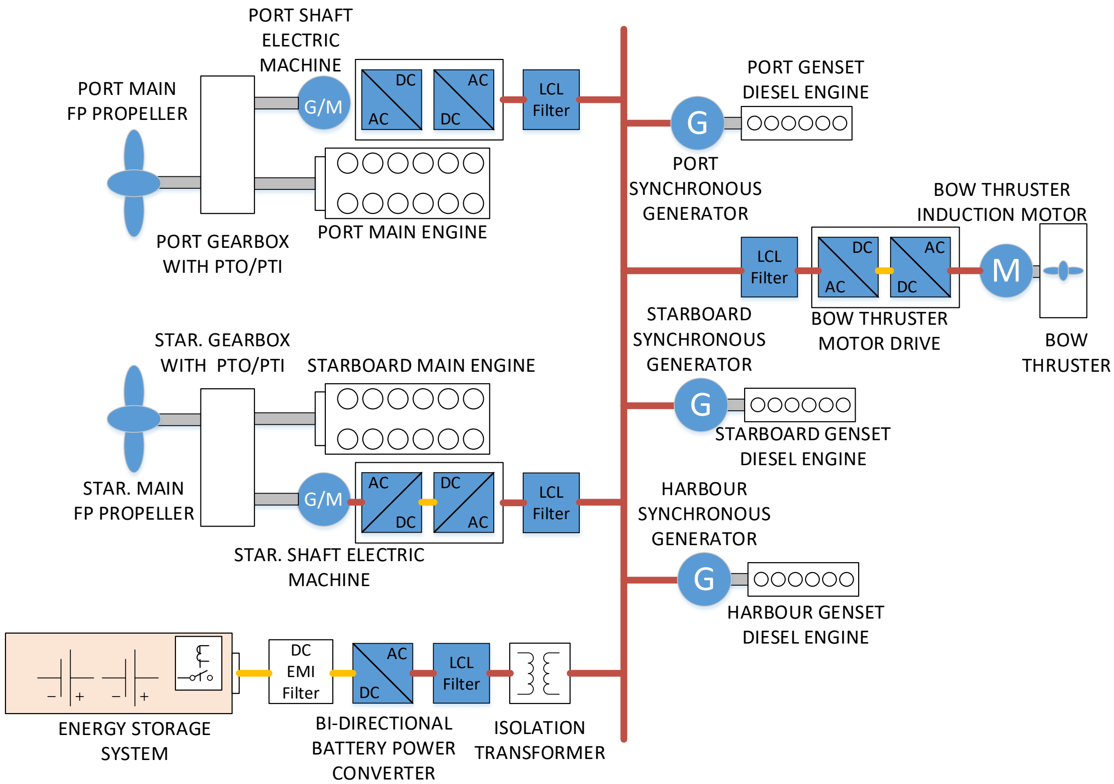

Figure 20 PTO/PTI Hybrid Propulsion System Diagram

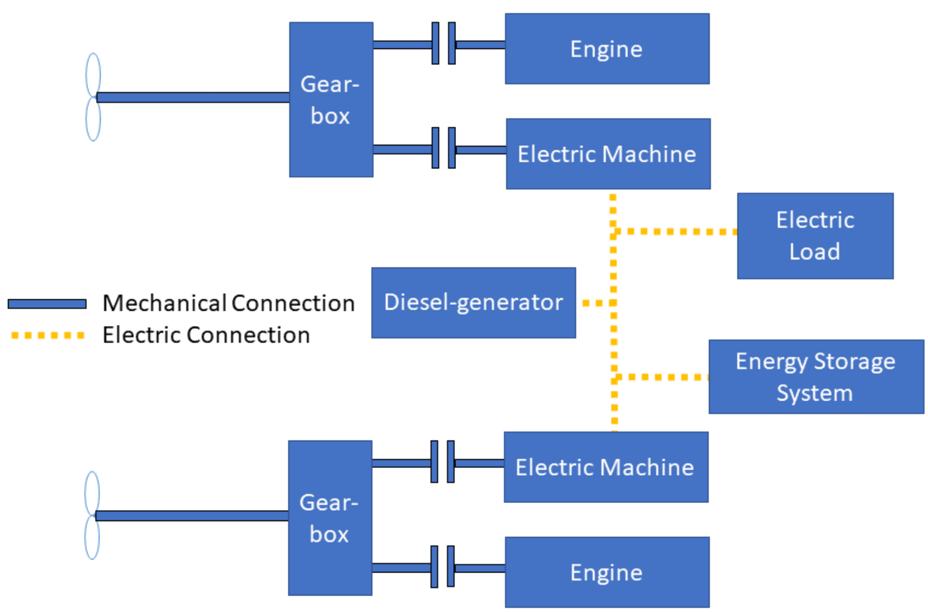

Figure 21 PTO/PTI Hybrid Architecture Diagram

3.4. Power Control and Energy Management Strategy (EMS) Block

The hybrid propulsion systems have more degree of freedom compared to the conventional diesel-mechanical direct drive propulsion systems. The multiple freedom system turns the original optimal design problem into a design optimization and optimal control problem, as more power and energy sources and intelligent controllers are integrated into the system. In the original setup, the performance of the ship is fixed, so long as the ship's hull, propellers, primer movers, and architecture are selected. However, the unique hybrid architecture makes it possible for fuel converters to operate in different feasible regions, which leads to different fuel rates. To find the optimal operation points for each step, a high-level intelligent ship power control and energy management strategy controller becomes necessary. The EMS significantly enhances the flexibility of the ship as it is possible for the vessel to perform an optimal operation for different tasks without going through a refit and optimization on its operations.

In this study, the energy management strategy controller is designed to manage the propulsion power flow split ratio between engines and electric machines. The supervisory controller is necessary for a complex hybrid propulsion system together with many different operation states at a high level, which ensures the hybrid system stability and the control logic consistently. This EMS controller receives power demands and splits the power between different power sources. It also manages the energy source distributions among diesel generators, ESS, and PTO/shaft generators in real-time. The controller also needs to monitor and control the ESS so that the system never executed boundary, avoid overcharge, and completely depleting the battery as the Li-ion battery ESS is embedded into the hybrid-electric propulsion system.

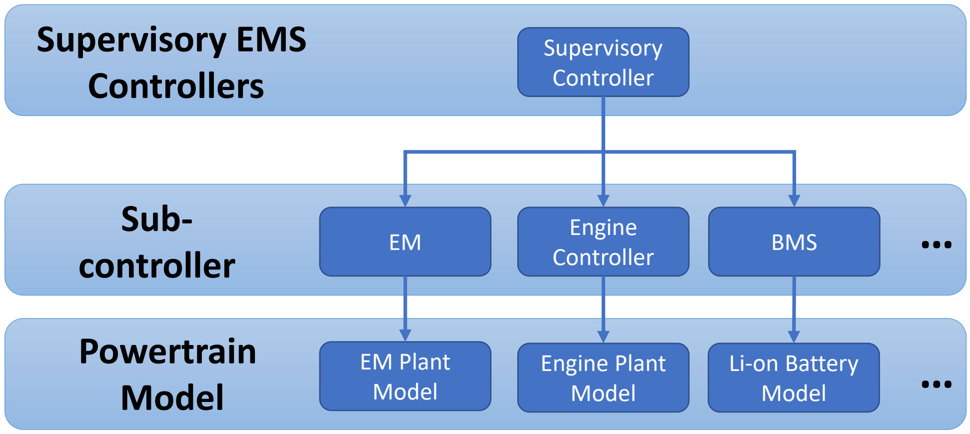

Figure 22 High-level Supervisory Controller Diagram

The proposed ship power control and energy management strategy module contain a supervisory controller. Typically, the hybrid propulsion system on land vehicles and marine vessels has many large devices such as engines, electric machines, generators, etc. Most of those devices have their controllers, and this high-level controller only generates the references and guidelines for sub-blocks (engine. EM, etc.). For example, instead of giving detailed control sequences, the EMS controls the EM only by sending the motor output power demand. The inside of EMS contains several blocks, such as engine on-off control block, mode selection block, etc.

3.5. Benchmark Mechanical Propulsion System and Simulation Results

This section illustrates the simulation results from a conventional diesel-mechanical direct-drive ship simulator, as this type of the ship is most common among all four propulsion system configurations. The characteristics of the powertrain parameters are shown in Table 7.

Table 7 Conventional Diesel Mechanic Ship Characteristics

Diesel Engine	630 kW × 2
Diesel Generator	160 kW × 2
Gearbox Ratio	4.63:1

The time-varying operation profile is presented in Figure 7, Figure 9, and Figure 10, and is used for all the simulations in this work. The conventional ship has a univocal relation between the power generated by each prime movers and propulsion power at thrusters. Thus, the controller simply needs to map the power requests from the operation profile to the corresponding engine controller. The electric load included all the electrical power demand during the operation, and the onboard diesel generator sets provide electricity. A smaller engine (compare to MV Tachek) is chosen since the original (before the life-extension project in 2013) ship equipped with a 650kW diesel engine (Model: CAT D398). The simulation result is presented in Table 8.

Table 8 Simulation Result for Conventional Diesel-mechanical Ship

Fuel Consumption	165.53 L
HC	3.32 Kg
CO	0.75 Kg
NO_X	22.56 Kg
Engine Operation Time (STBD/PORT/Die-Gen)	3 × 6000 sec

The engine operation time stands for the total engine operation time for each engine and the diesel generator in the unit of second. In a conventional setup, the diesel engine needs to supply the hotel during the operation; thus, it is always turned on.

This mechanical direct-drive ship consumes a total of 165.53 L diesel in a round trip. As shown in Figure 23, the green points in the figure represent the engine operation point during the crossing. Each point stands for a specified efficiency/emission at corresponding engine speed and torque. In this mechanical direct-drive configuration, the propulsion power is proportional to the prime mover's output power. The engine operates inefficiently when the propulsion power demand is low (blue circle), also leading to an insufficient burring of fuel with high HC and CO emissions, as shown in Figure 25 and Figure 26. This ship doesn't produce too much CO emission as it does not operate near maximum torque. Diesel engines typically get better efficiency at the middle to high load range. The engine is not able to operate at its efficient zone (red square zone) as the propulsion power demand is lower than the high-power demand thread. The engine consumes less fuel when idling, those idling speed and torque area also are in high pollution zone, thus should be avoided.

This ship is considered as benchmark case and compares with other ships in Chapter 4. Overall, the engine efficiency is relatively low sand produces more NO_X and HC.

It should be noticed that only Engine 1 is presented in the figure as Engine 2 (PORT) has a similar pattern to engine 1 (STBD).

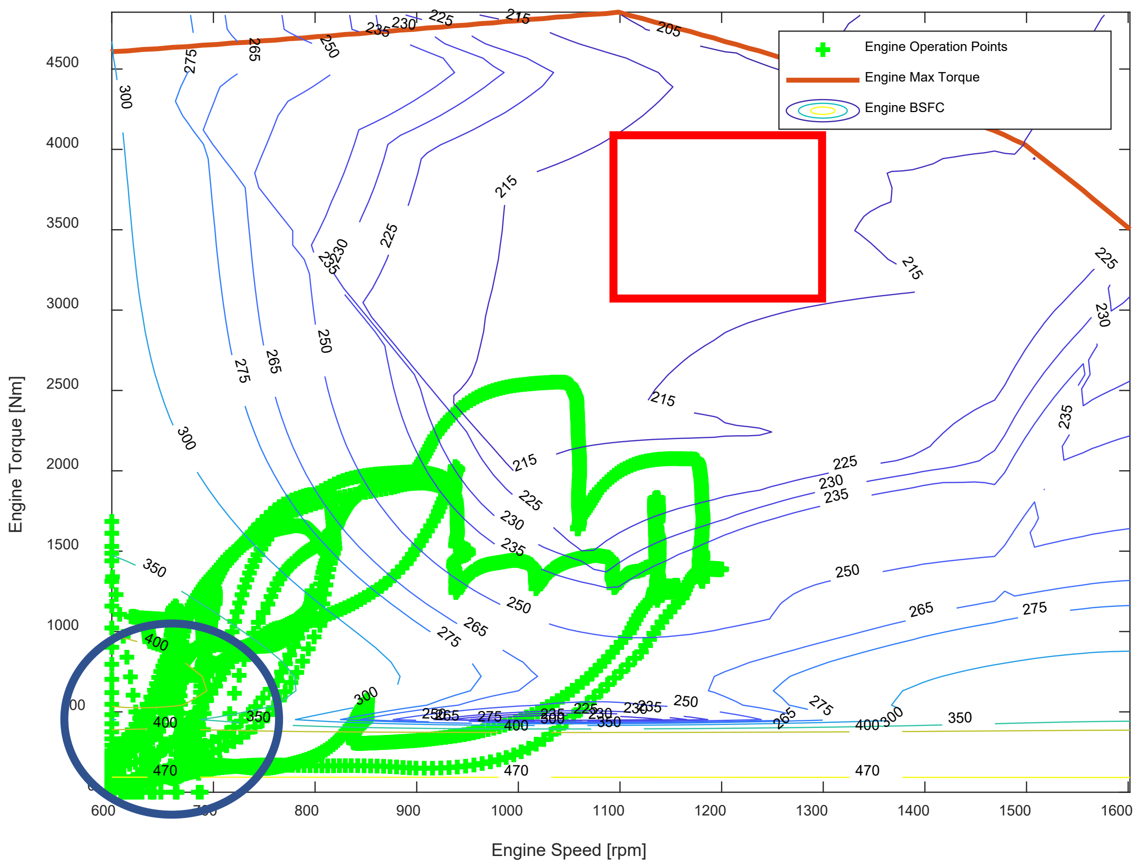

Figure 23 Engine 1 Operation Points and BSFC Map for Conventional Ship

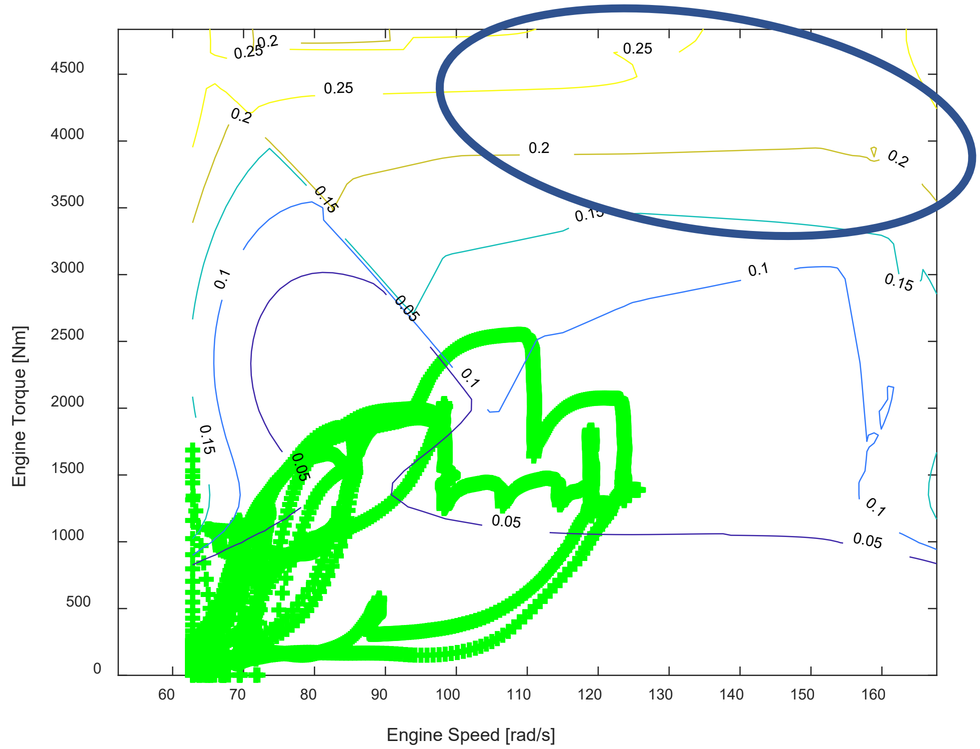

Figure 24 Engine 1 Operation Points and CO Map for Conventional Ship

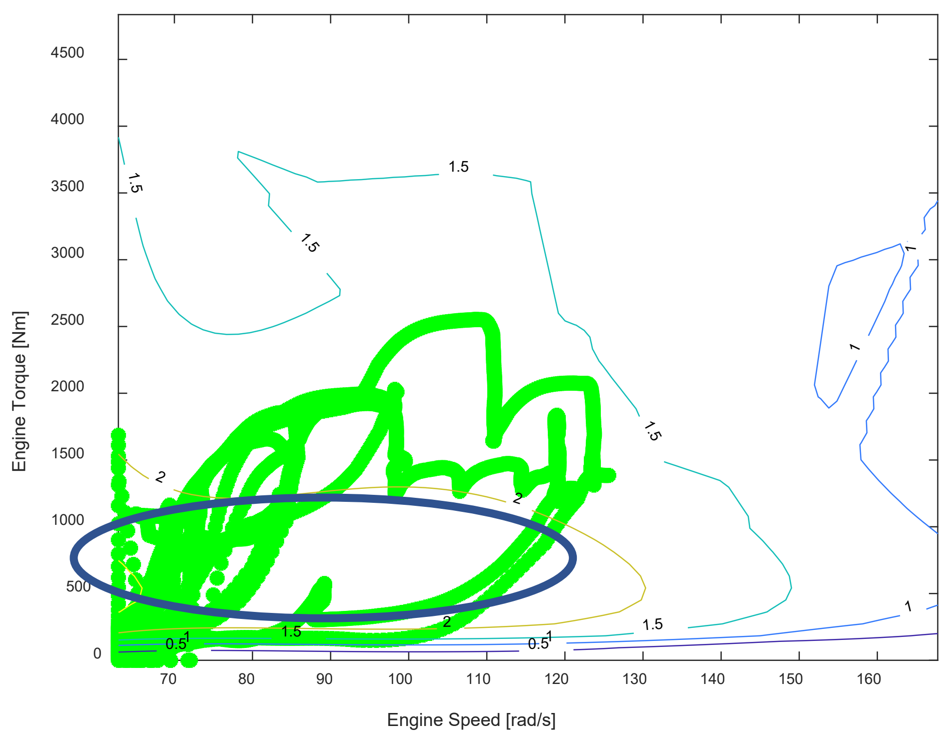

Figure 25 Engine 1 Operation Points and NO_x Map for Conventional Ship

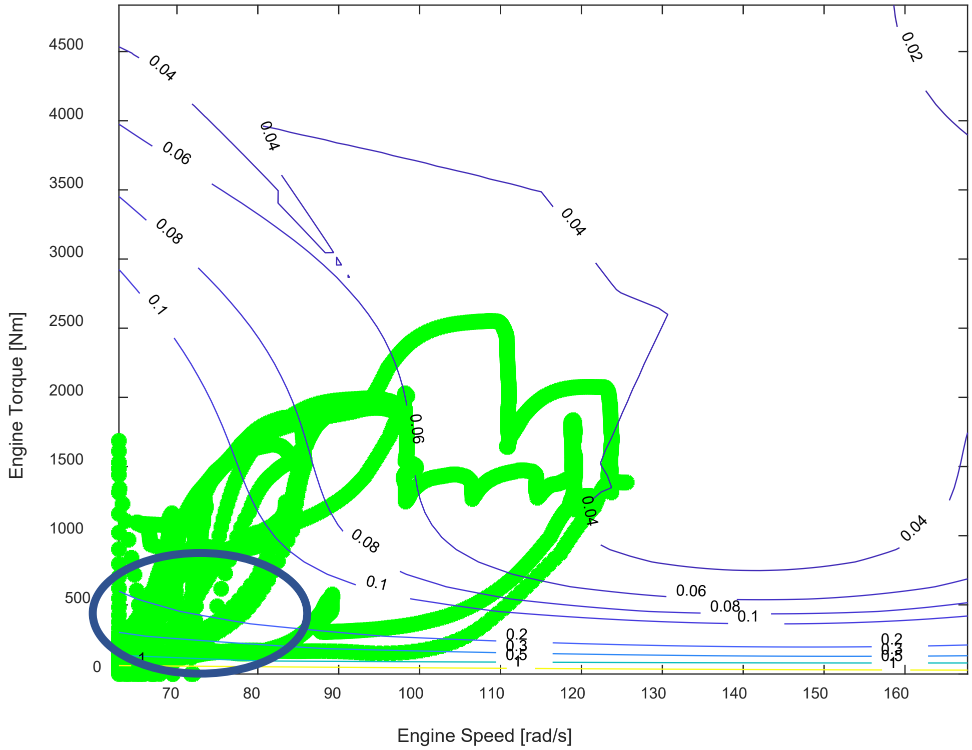

Figure 26 Engine 1 Operation Points and HC Map for Conventional Ship

Chapter 4 CONTROL OF HYBRID ELECTRIC PROPULSION SYSTEM

A hybrid electric propulsion system, different from the conventional diesel-mechanical and pure electric propulsion systems, has multiple power sources from the engine and the electric ESS. The propulsion system control, serving as a “smart operator,” is needed to determine the power split rate between the two sources in real-time. The hybrid electric marine propulsion system breaks the direct link between the propulsion power at the propellers and the power generated by the diesel engines. In the proposed parallel hybrid electric propulsion system, propulsion power could come in mechanical form from the main diesel engines, or in electrical form from the battery ESS or the diesel generator sets. Different splits of power could lead to different overall system performance and energy efficiency. A high-level supervisory controller for optimal power control and energy management is needed.

The goal of this chapter includes:

a) Investigating the potentials and difficulties of turning a conventional ship into a hybrid electric vessel
b) Studying different energy management strategies
c) Summarizing the learnings from this case study

The new and revised parallel hybrid electric propulsion system, as illustrated in Figure 4, has both PTI and PTO ability. The Electric Machines (EM), or Motor/Generator (M/G), connected to the main diesel engines, can serve as both motors and generators, to support the full hybrid electric propulsion. The powertrain parameters of the newly proposed hybrid ship are given in Table 10. The minor powertrain system change required different powertrain system components and system control strategies.

4.1. Technical Challenges in Developing Optimal Power Control and Energy Management Strategy Controllers

A hybrid electric propulsion system is proposed as a solution, and the modelling platform is presented as discussed in the previous chapters to face the ever-increasing pressure on the marine industry to reduce its environmental impacts and improve fuel economy.

The hybrid propulsion system has more degrees of freedom and can operate in different modes. To understand the complexity of the hybrid ship operation conditions, first, a simplified hybrid ship diagram is illustrated in Figure 27. The flexible operations of the PTO/PTI hybrid architecture provide different operation modes for each propulsion system, and the combination of the operation modes results in a complex discussion making and energy management problem. To better understand the system, each system can be classified into four distinct categories, as shown in Table 9. Instead of using PTO/PTI, the operation mode is subdivided into several categories.

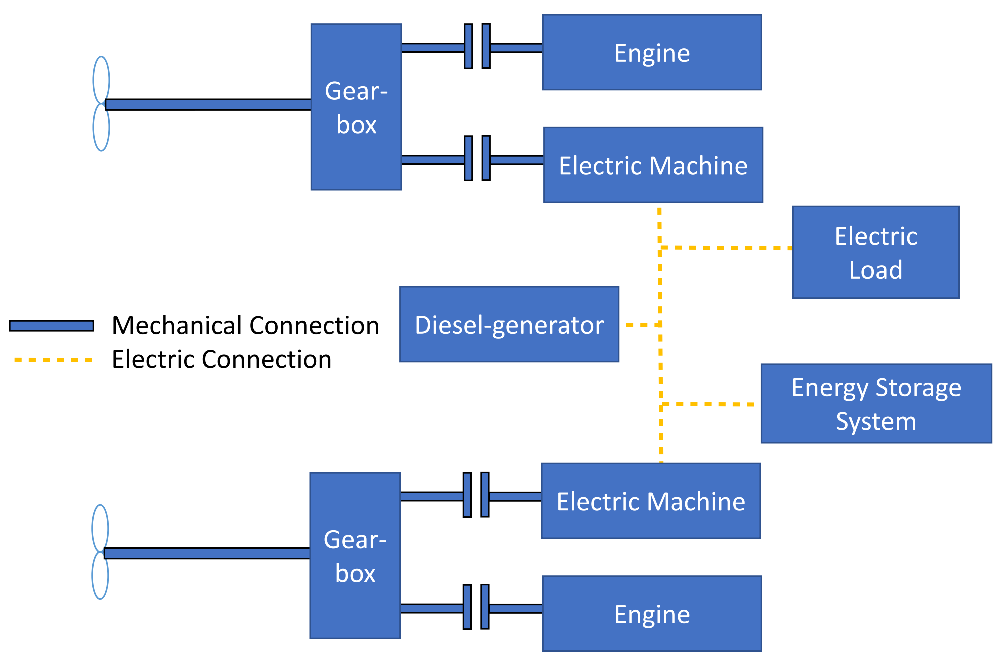

Figure 27 PTO/PTI Hybrid Architecture Diagram

Table 9 Propulsion System Operation Mode

Propulsion System Operation Mode	Power Flow Diagram	Propulsion Energy Source
Direct diesel-mechanical	Figure 28 Direct Diesel-mechanical Mode Power Flow	1) Engine
Motor Assistant	Figure 29 Motor Assistant Mode Power Flow	2) ESS 3) Diesel Generator Sets 4) Shaft Generator 5) Engine 6) Combine of all above
Peak Shaving	Figure 30 Peak Shaving Mode Power Flow	7) Engine
Pure Electric	Figure 31 Pure Electric Mode Power Flow	8) ESS 9) Diesel Generator Sets 10) Shaft Generator 11) Combine of all above

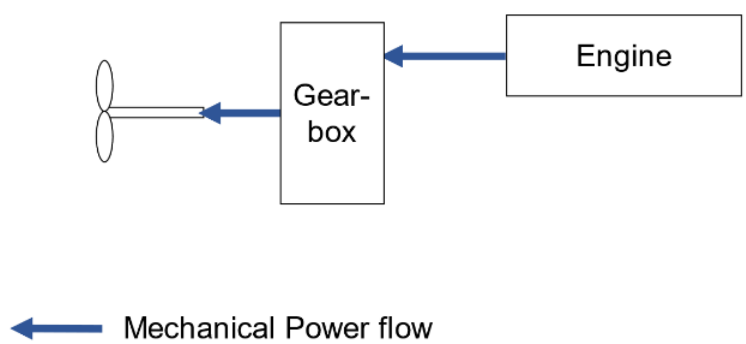

Figure 28 Direct Diesel-mechanical Mode Power Flow

In each operation mode, the energy source may vary and need to be determined according to the power demand and overall system conditions.

In direct diesel-mechanical (mech) mode, the ship operates as a conventional direct diesel-mechanical vessel, the propulsion system is decoupled to the electric propulsion system, and the prime mover (diesel engine) is the only power source that drives the propeller.

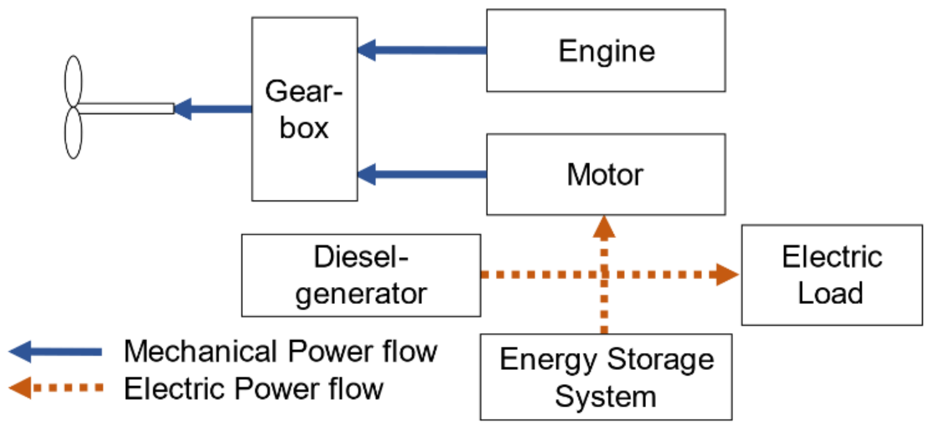

Figure 29 Motor Assistant Mode Power Flow

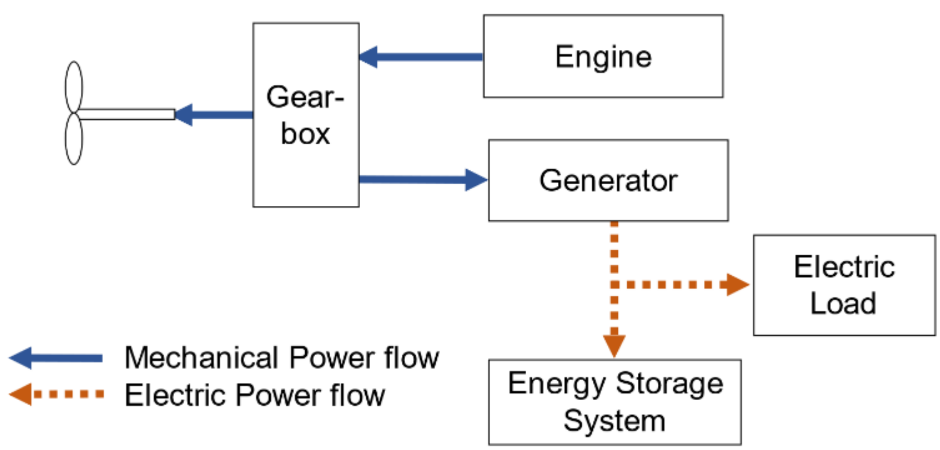

Figure 30 Peak Shaving Mode Power Flow

In motor assistant mode, the engine operates at optimal points, and the electric machine kicks in and provides extra power when needed. Sometimes the engine generates more mechanical power than the propulsion need so that the engine can avoid operating in undesired conditions at inefficient, pollution zone, as shown in Figure 11, Figure 12, Figure 13, and Figure 14. The shaft generator can absorb extra power and maintain the needed propulsion power, in the meantime, charging the ESS and providing electric power. This mode is assigned to the peak shaving mode, as in Figure 30.

As large battery banks and powerful electric machines are integrated into the hybrid system, the propulsion system is also capable of operating in pure electric mode. In this mode, the propulsion system works similarly to a diesel-electric propulsion system. However, the prime energy source is determined by the controller, and the power could come from the ESS, onboard diesel generators or the other main diesel engines, or the combination of all above.

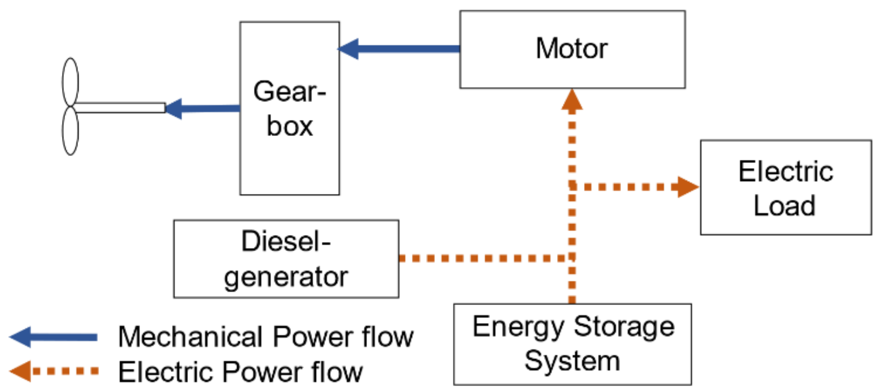

Figure 31 Pure Electric Mode Power Flow

The power flow for each operation mode is presented in Figure 28, Figure 29, Figure 30, and Figure 31, respectively. It should be noticed that only one shaft line is shown, all powerlines share the same ESS and are connected through electric links.

The goal of the ship power control and energy management strategy studies can be summarized as:

a) Maintaining the system running at a steady-state to retain the level SOC, operate the EMs/engines at the desired range, and deliver sufficient propulsion power to the propellers, etc.

b) Minimizing fuel consumption and exploring the potentials for emission reduction.

In this chapter, two different energy management strategies for hybrid propulsion systems are introduced, and the simulation result is analyzed, and the advantages and drawbacks for different EMSs are investigated. The characteristics of the studied hybrid ship are presented in Table 10.

Table 10 Hybrid Ship Propulsion System Characteristics

Diesel Engine	630 kW × 2
Shaft Generator	160 kW × 2
Diesel Generator	160 kW × 2
Gearbox Ratio	4.63:1
Energy Storage System	6s6p A123 Battery Module

4.2. Rule-Based Power Control and Energy Management Strategy

A rule-based supervisor controller is a commonly used method to design the controllers for hybrid cars. This method controls the power flow by applying the control rules defined by experts of the field, according to the instantaneous operation conditions. In this study, the main control goals are to manage the energy flow and secure the system by operating in a feasible region. Typically, a rule-based controller is constructed in the form of the state-flow chart. Powertrain components' characteristics and efficiency maps are used when implementing the controller.

As a rule-based controller only relies on instantaneous ship operation conditions and predefine knowledge, recorded by the control rules. The primary benefit of using a rule-based controller is the ease of implementation in real-time-control since local constraints such as EM/engine rated power can be quickly taken into consideration when implementing the controller. The controller applies the control rules and forces the system to operate at desired conditions. This result is achieved by running the engine and motor at the high-efficiency region to make better fuel/energy saving, reducing the engine operating time by turning the engine off when applicable, and running the ESS genteelly to extend battery life and reducing the lifecycle cost. Those rules typically are easy and straightforward but can be extended to a complex knowledge library by adding more rules to the controller. Heuristic human experience from the captain and engineer's expertise and software simulation using dynamic programming can be used to help to deduce the desired control rules and to derive prior knowledge as guidelines.

For real-time control applications, the SOC of the battery ESS cannot be the same due to the variations of the operation and powertrain configuration. At the end of each operation cycle, the onboard diesel generators are used to charge the ESS until the SOC reaches the initial state, to fairly compare the simulation results from different powertrain configurations. This portion of fuel consumption is also calculated and is added to the total fuel consumption. Thus, the complete fuel consumption formulation can be summarized as

$$fuel_{all} = fuel_{cycle} + f_{DG}(E_{ess}) \tag{4-1}$$

where $fuel_{cycle}$ is the main engines' fuel consumption during the operation, E_{ess} is the total energy needed to charge the ESS to the initial SOC, f_{DF} is the model for calculating the fuel consumption for producing the energy in the E_{ess} using vessel's diesel generator. The $fuel_{all}$ represents the total fuel consumption.

4.2.1. Apply Rule-Based Controller on PTO/PTI Hybrid Powertrain

One of the rule-based control methods for this type of application is commonly called power follower strategy. The power follower strategies control by operating the engines as the primary power source and using the EMs and the ESS as the power reservoir. The EMs assist the engine when the power demand is greater than the optimal engine power, allowing the engine to operate at the optimal speed and torque. The EMs also absorb the extra power produced by the engine to charge the battery ESS when the engine working at its optimal speed and torque produces more than needed propulsion power. Other control logic is also added to improve the stability and safety of the ship.

A few simple control rules are deduced as summarized below:

1) When SOC is higher than 0.9:
    a. Use ESS as the primary energy source, switch the ship operation mode among mech mode, motor assistant mode, and pure electric mode.
    b. Avoid overcharging the ESS.
2) When SOC is between 0.35 and 0.9:
    a. Switch amount all operation mode freely and force the engine following an optimal curve (Highest efficiency curve in this study). The EMs operate as peak shaving devices, generating electricity, or kick in and provide extra propulsion power when the torque demand is higher than the optimal torque.
    b. Maintain the SOC at a specified range.

3) When SOC is lower than 0.35:
   a. Use fossil fuel as the primary energy source. Switch the mode between mech mode and peak shaving mode.
   b. Switch to motor assistant mode to supply sufficient propulsion power when there is high power demand and start diesel generator sets (operates at most efficient point regardless of the instantaneous electric power demand) if needed. The electrical power is mainly used to support the motor and electrical load. Still, the rest of the power can be used to charge the ESS.
   c. Avoid draining the battery completely.

The optimal operation curve of the engine is pre-defined to improve fuel consumption. The maximum efficiency points of the curve at different speeds are determined in advance. This EMS is implemented in MATLAB using State-Flow Chart and Simulink. The *ENG_ON_OFF_Control* block is used to control the engine on-off logic and to avoid turning on/off the engine frequently.

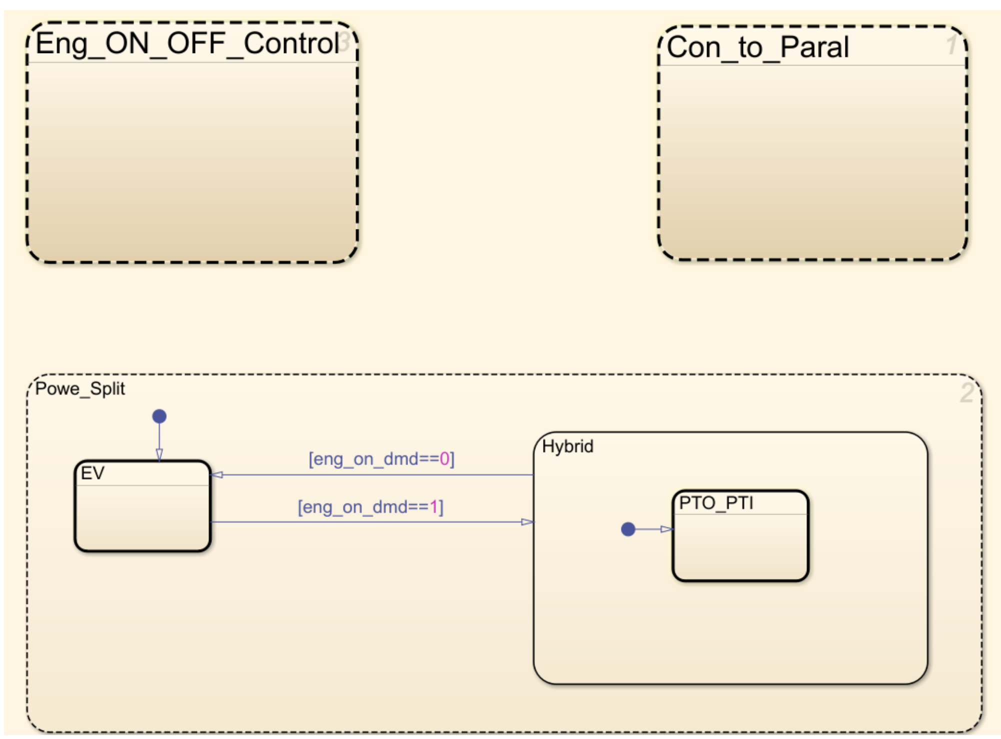

Figure 32 Rule-based State-flow Chart

4.2.2. Rule-Based Controller Simulation Result

The control law described above performs as expected and improves fuel consumption by 10.1%. As shown in Figure 33, the propulsion system is able to follow the propulsion demand and provide sufficient propulsion power. Although the ESS SOC never falls into 'low' in this study, the EMS does force the ship to operate in pure electric mode and motor assistant mode when SOC is high. Figure 34 presents the SOC variation during the operation. The selected ESS is relatively large for this case (proposed power follower rule-based hybrid electric ships); and when the ship switches to electric vessel mode, the controller only remains in that mode for a short period, since the EM's rated power is low and can no longer meet the requirement on the propulsion power increased, thus, the ESS SOC does not have the opportunity to reach the lower bound, but only varies between higher bound and somewhere near 0.5. Despite that, the result correlates to the proposed rules. The electric machine operation mode is determined by EMS based on SOC and ship instantaneous operation conditions. The simulation result indicates that the EMs mainly operate as generators during sailing. However, the ship tends to run as a pure electric ship when approaching/leaving docks, and only uses EMs when applicable, as the propulsion power demands during this process are significantly lower than power demands during the sailing. Figure 37 illustrates the change in engine operation points (compares to a MECH ship). The result shows that the engine operation points are shifted to a more efficient regime, hence avoiding operating in a low load zone. Figure 35 and Figure 36 present the EM's output power and diesel engine's output power, respectively. The engine on/off module performs as expected, and the engine is completely turned off when applicable. Figure 35 demonstrates that the electric machines only kick in and provide propulsion power when needed, and absorb the extra energy from engines, supporting the hotel load and storing them in the ESS.

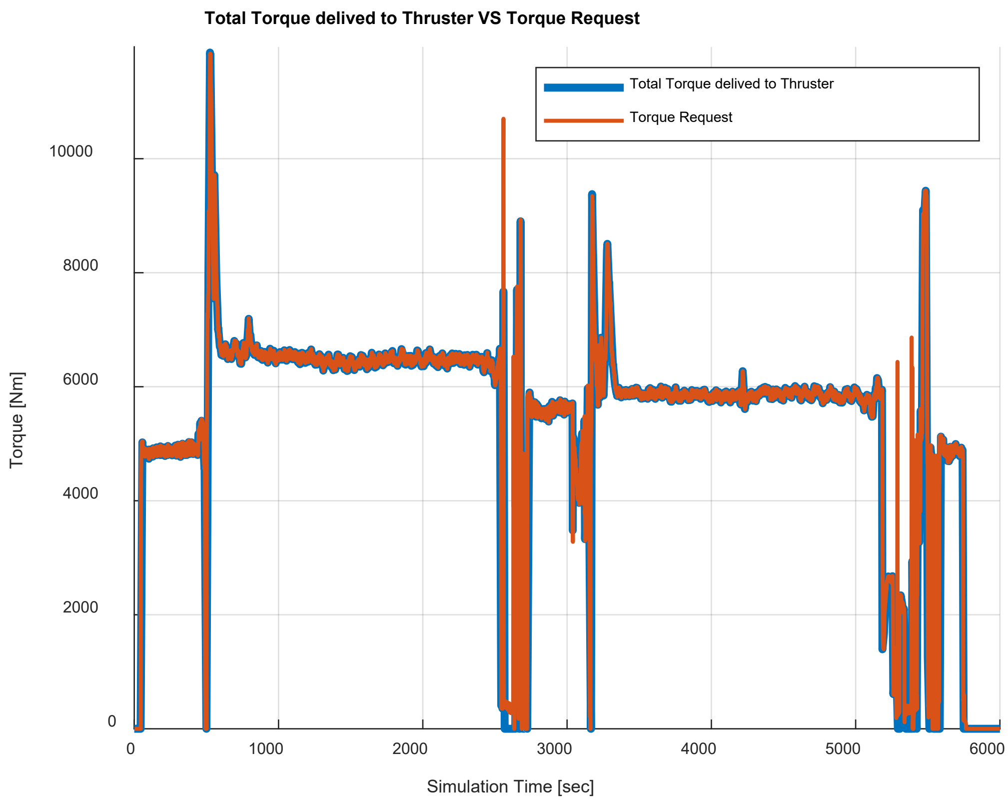

Figure 33 Cycle Power Profile VS Power Delivered to Thrusters

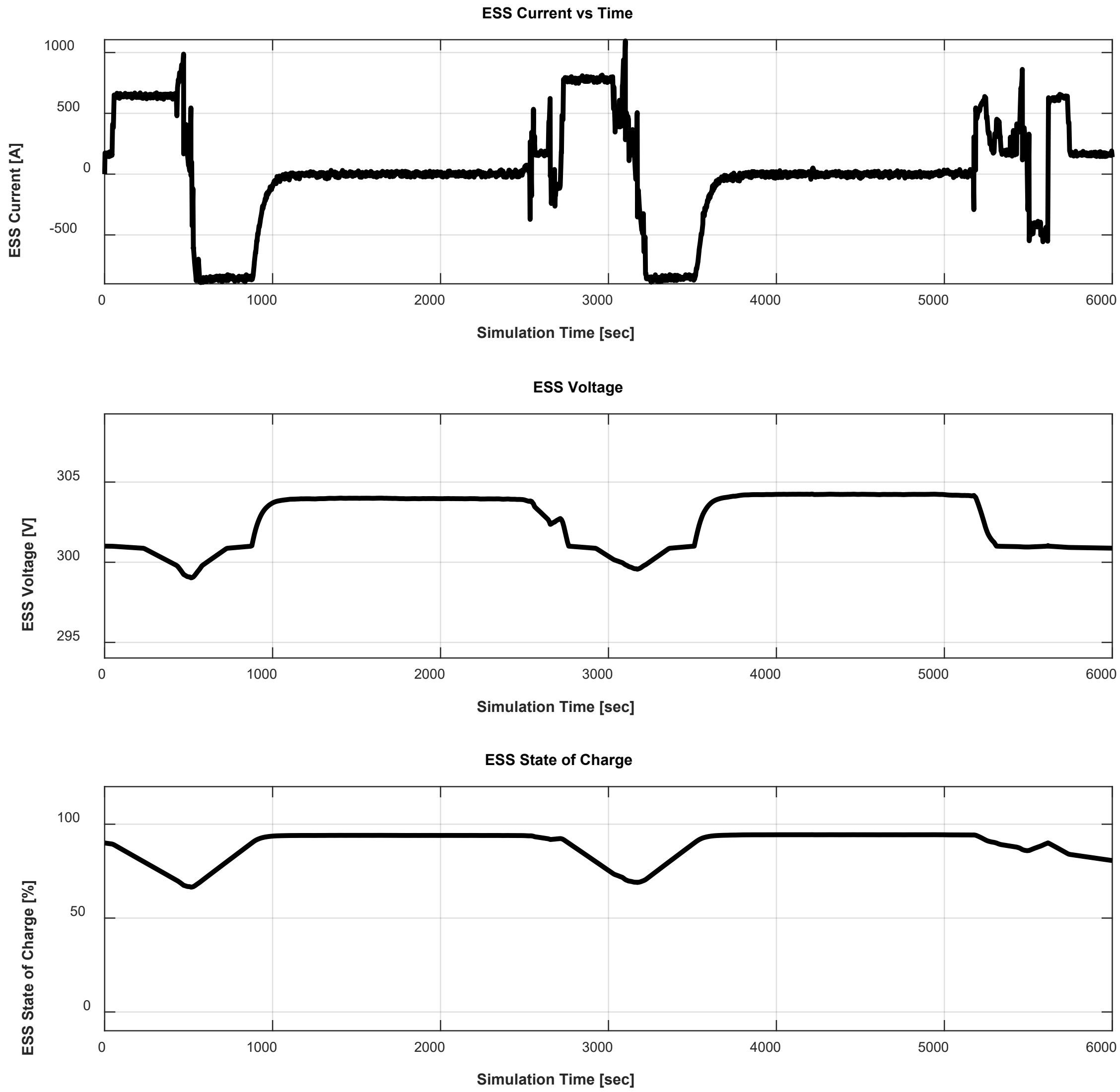

Figure 34 ESS Current, Voltage and SOC

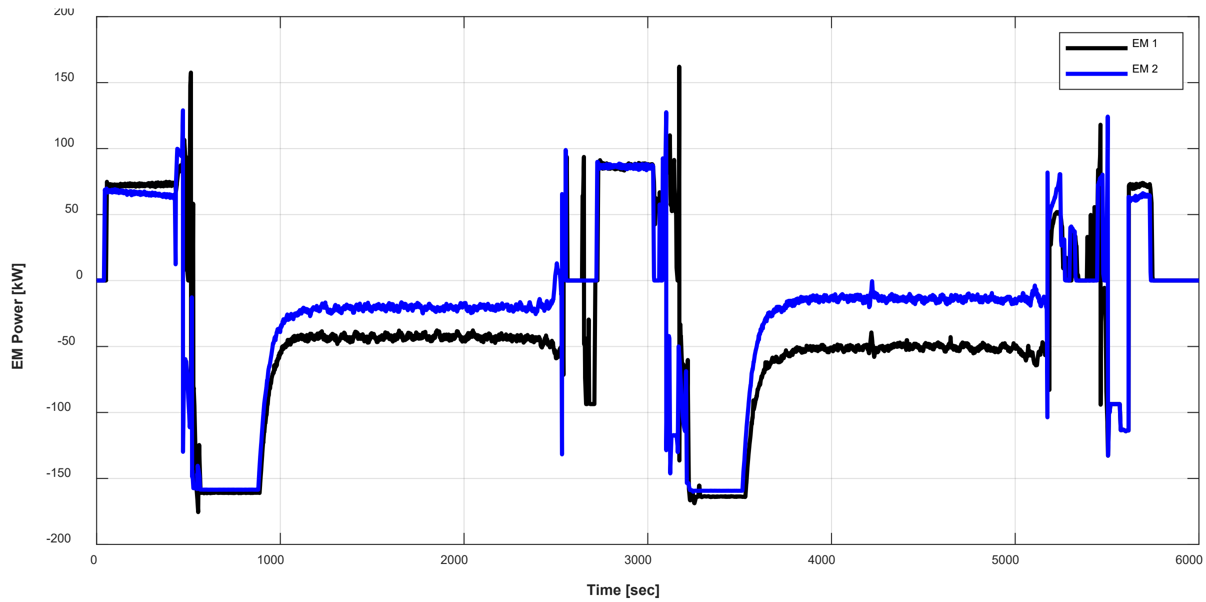

Figure 35 Electric Machines' Power (Generator: Negative; Motor: Positive)

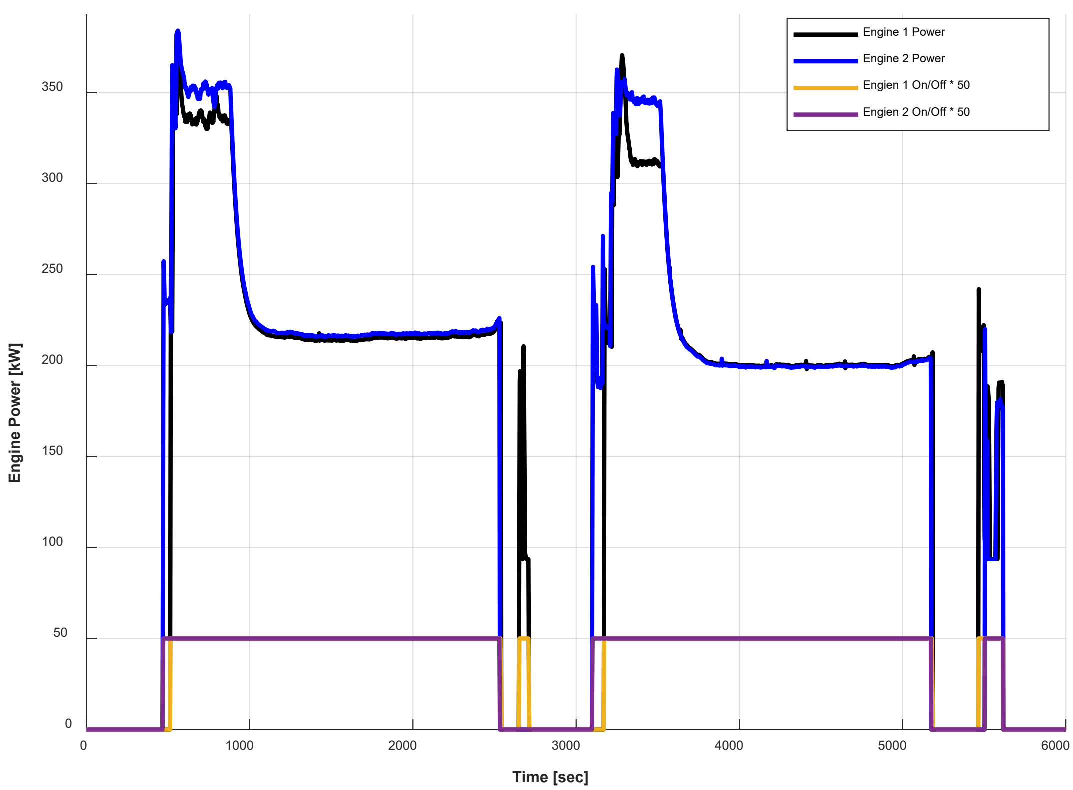

Figure 36 Engines' Power

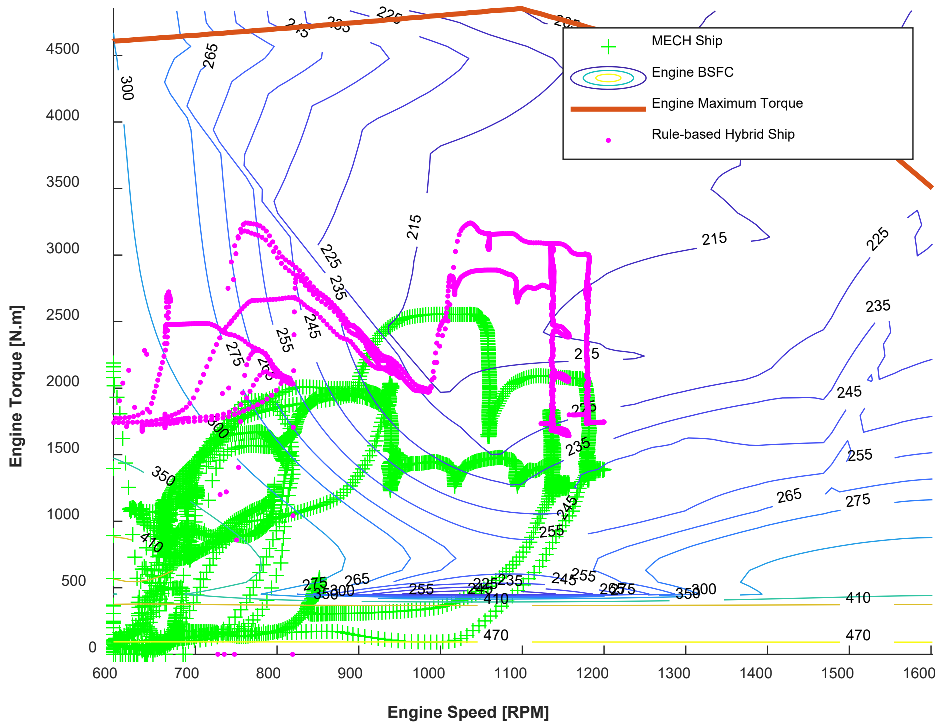

Figure 37 Engine 1 Operation Points

The fuel consumption and emissions are presented in Table 12.

Table 11 Simulation Result for Rule-based EMS Hybrid Ship

	Baseline	RB Hybrid Ship	Improvement
Fuel Consumption	165.53 L	148.75 L	10.1%
CO	0.75 Kg	0.65 Kg	10.7%
NO_x	22.56 Kg	13.46 Kg	38.7%
HC	3.32 Kg	0.36 Kg	88.6%
Engine-On Time	6000×3	4177 / 4198 / 109	29.1% / 29.2% / 95.4%

Compared to the original architecture, there is a significant improvement in emission reduction due to the shifting of the engine's major operation region. However, reducing emissions is not a significant concern in this study. The engine operation points corresponding to emission maps are presented in Figure 38, Figure 39, and Figure 40. By comparing the simulation result of RB hybrid ship to the MECH ship, the ship, the proposed controller, allows the engine to avoid operating at the high HC zone, as shown in Figure 38.

The simulation results indicate that the rule-based EMS can easily modify the engine operation points and even achieve the optimal solution at some points. However, this EMS cannot guarantee the propulsion system operates at its highest efficiency regime, as only the engine's operating efficiency is considered in the RB controller. This type of controller only achieves a suboptimal control action for the entire mission cycle; thus, the controller is not optimized. On the other hand, rule-based controllers can achieve results close to the optimal results. Still, the knowledge library is messy and complicated (to implement hundreds of thousands of rules), is challenging to adapt to different ships, and is ill-adapt to different operators as well as various operation profile.

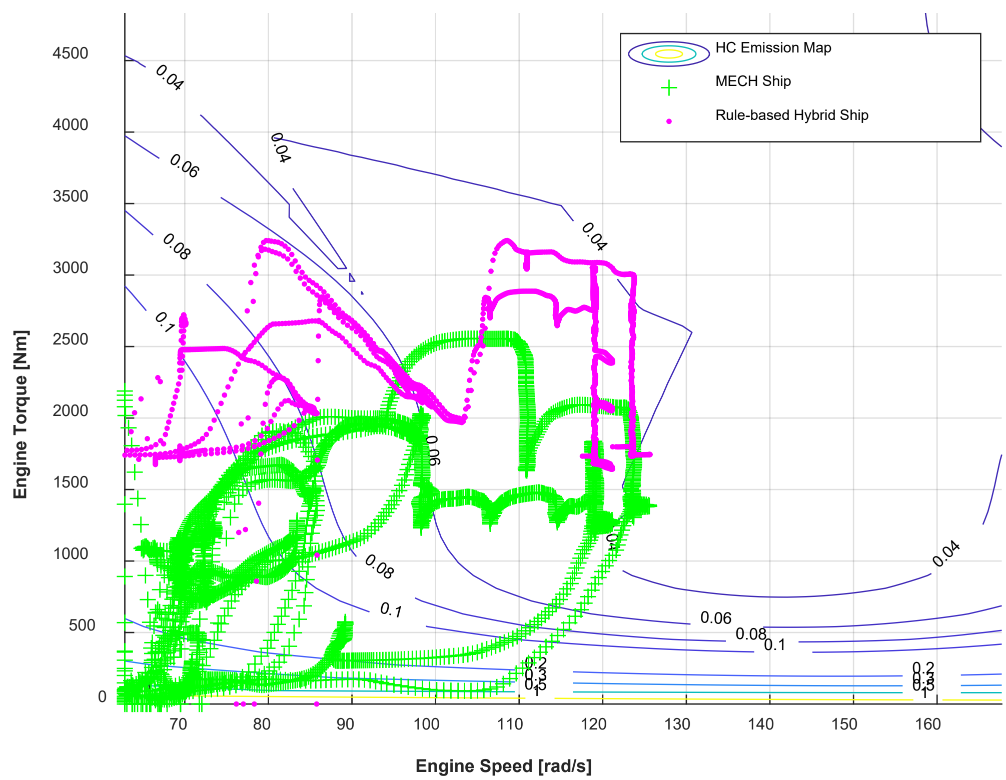

Figure 38 Engine 1 HC Maps and Operation Points

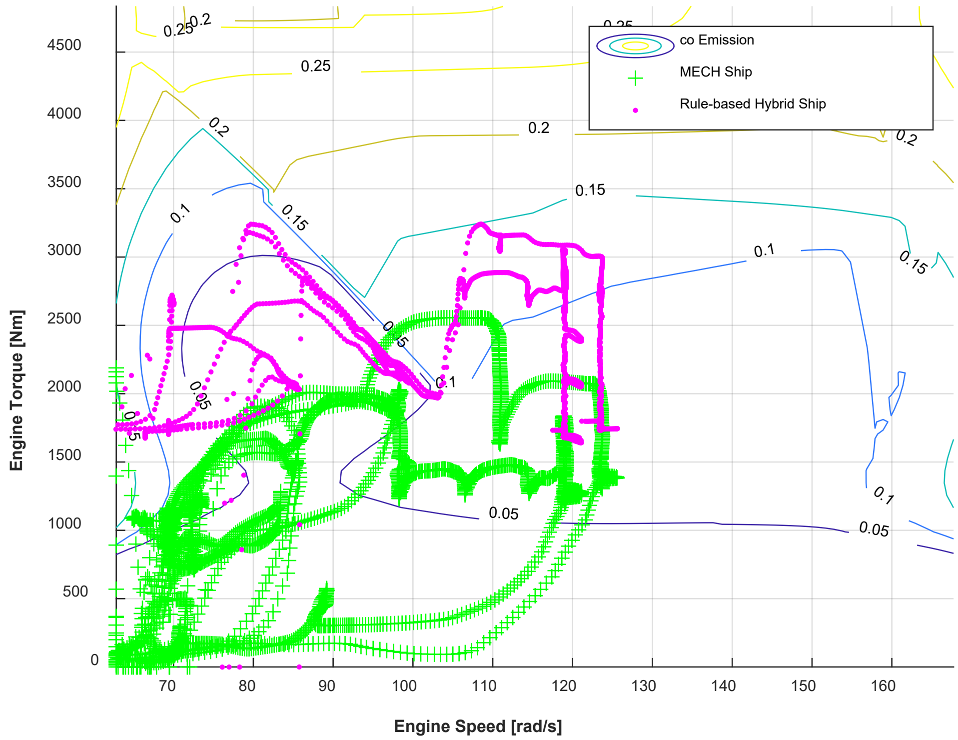

Figure 39 Engine 1 CO Maps and Operation Points

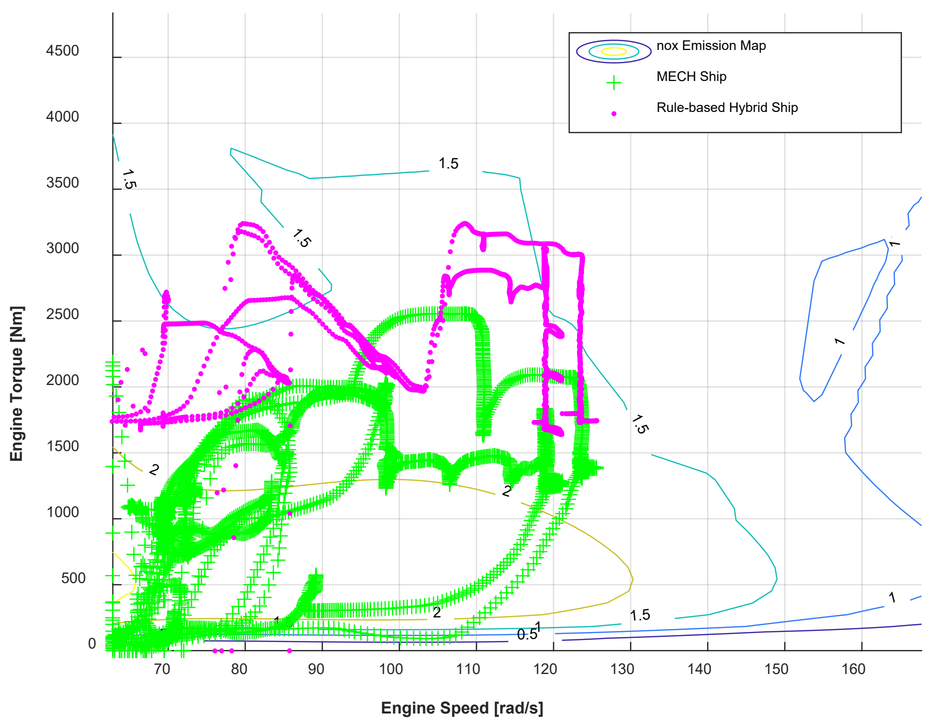

Figure 40 Engine 1 NO_x Maps and Operation Points

4.3. Optimization-based Power Control and Energy Management Strategy

The rule-based EMS has many advantages due to its simplicity. However, the system efficiency is not optimized, as only the engine efficiency is considered, and the result shows that the rule-based EMS does produce better results compared to the conventional ship. Nevertheless, minimization of the fuel consumption or emission of a hybrid vessel is, essentially, an optimization problem.

4.3.1. Benefits of Using Opt-Based EMS Compared to Rule-based EMS

Typically, a rule-based energy management strategy relies on current and historical driving conditions to achieve an excellent real-time control strategy, while global optimal optimization-based EMS requires future driving information to identify the optimal solution. Applying a real-time optimization-based energy management strategy is a challenge. Several different controllers have been designed [9].

The objective of the optimal control problem in this study is to achieve minimal fuel consumption. The applied optimization-based controller in this subsection is called an equivalent consumption minimization strategy [35], [36]. The idea of the ECMS can be explained as follows: assume there exist two fuel tanks in the propulsion system (a fossil fuel oil tank, and a virtual fuel tank). The fossil fuel oil tank only provides diesel fuel; however, the virtual fuel tank can provide virtual fuel in the form of electric energy and can reverse the fuel direction by charging the buffer (ESS in this case). To achieve the best performance (minimizing fuel consumption), an ideal optimal controller splits the power flow in the system based on SOC, power demands, and mechanical limits. This method reduces the complexity of global optimization to a local optimization problem by considering a shorter period (by only requiring information regarding the past and present, instead of the entire trip); thus, future operation conditions are not needed.

In this setup, all the energy is from fossil fuels (no shore charging capability); that is to say, to produce the same amount of energy in each crossing, engine efficiency will be the main factor that affects the overall fuel consumption. Hence, the rule-based controller focuses on operating the engine efficiently, as introduced in 4.2. Other power loss, such as DC/DC converter’s efficiency loss, mechanical loss, and generator’s efficiency loss, also played a significant role during energy conversion and should be taken into consideration. The ESS operates as a buffer: each unit of electric energy that comes from the ESS needs to be replenished in advance or later using the energy from fossil fuel (through ICE and generator); thus, the fuel rate does not reflect the actual instantaneous fuel rate corresponding to propulsion needs anymore. To put it another way, assume there exists a virtual fuel consumption associated with the use of the battery, which can be positive or negative. The sum of the actual fuel consumption of ICEs and the victual fuel consumption is the equivalent fuel consumption, which can be higher or smaller than the actual instantaneous fuel consumption of diesel engines. Finally, the equivalent fuel consumption is used to evaluate the overall performance in each time step.

4.3.2. Apply ECMS on PTO/PTI Hybrid Electric Vessel

The equivalent fuel consumption rate is defined in Eq. (4-2), consisting of two parts: the instantaneous fuel consumption rate and the virtual fuel consumption rate as further described in Eq. (4-3). The virtual fuel consumption rate accounts for electric energy consumption from the ESS. S_b represents the conversion efficiency between electric power and fuel consumption rate, and Q_{lhv} is the lower heating value of the fuel, and $P_{batt}(t)$ is the ESS power at time t. The aforementioned gives the virtual fuel rate $\dot{m}_{ress}$. $\dot{m}_f$ stands for actual fuel rates of main engines. A penalty function $P(SOC)$, which is negligible whenever the instantaneous SOC differs from the target SOC, is added to adjust the equivalent fuel consumption under the same load condition and to maintain the SOC at a specified range by increasing the nonlinearity of the equivalent fuel consumption, as seen in Figure 41. This penalty is critical in maintaining the SOC between the boundary [37]. A penalty function, in the form shown in Figure 43, is used to incorporate the nonlinearity influencing factor.

$$f(t) = \frac{dm_{f,eqv}(t)}{dt} = \frac{dm_{ress}}{dt} \cdot P(SOC) + \frac{dm_f(t)}{dt} \tag{4-2}$$

$$\frac{dm_{ress}}{dt} = \frac{S_b}{Q_{lhv}} P_{batt}(t) \tag{4-3}$$

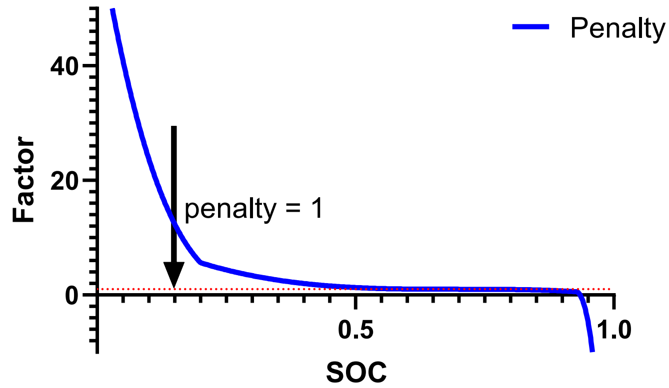

Figure 41 Penalty Function

The optimal power split ratio of the system can be obtained using the optimization problem formulated as the following, as long as the factors S_b are correctly calibrated.

$$\min f(t)$$

$$\text{subject to} \quad \begin{gathered} P_{min} \leq P \leq P_{max} \\ T_{min} \leq T \leq T_{max} \\ SOC_{lb} \leq SOC \leq SOC_{ub} \end{gathered} \tag{4-4}$$

The engine on/off control is implemented to avoid turning on and off the engine too frequently. A mode switch module is also implemented so that minimum operating time is achieved for each operation mode, which inhibits the possibility of switching between each operation mode frequently.

4.3.3. Optimization-Based Controller Simulation Result

Table 12 compares the fuel consumption and emissions between an ECMS-based hybrid electric ship and a conventional ship.

The EMCS-based EMS resulted in improved ship operation. The fuel consumption of the EMCS based hybrid ship declined from 165.54 L of the mechanically propelled vessel to 142.84 L, with a proportional reduction of CO_2 emissions.

Table 12 Simulation Result for Optimization-based EMS Hybrid Ship

	Base Line	ECMS Hybrid Ship	Improvement
Fuel Consumption	165.53 L	142.84 L	13.7%
CO	0.75 Kg	0.6 Kg	20.0%
NO_x	22.56 Kg	12.14 Kg	46.2%
HC	3.32 Kg	0.57 Kg	82.8%
Engine ON Time	6000 / 6000 / 6000	3308 / 4138 / 1237	44.9% / 31.0% / 79.4%

Figure 42 indicates the improvements of Engine 1 operation, showing the engine operating in a more fuel-efficient region. The output power of the engine is presented in Figure 43, showing the engine turns on and off as expected, and the propulsion system operates in one mode for a minimum period of time before switching to another operation mode. The operations of the electric machines are illustrated in Figure 44 with mode switches based on battery SOC and propulsion power demand. As the motor is not capable of providing all the propulsion power during the crossing, the pure electric model is triggered only during docking for vehicle/passenger loading and unloading. Apart from the docking period, the ship operates in a combination of peak shaving mode and motor-assist mode. The output power on propeller shaft 2, as illustrated in Figure 43 and Figure 44, shows that the system operated in the peak shaving mode when applicable. Under this mode, the EM may charge the ESS, and drive the EM on the other propeller shaft. The stored energy may be used to propel the thruster and support services later. The controller forces the engine to operate at two highly efficient zones (900 RPM, 500 Nm and 1100 RPM, 3000 Nm). When operation within those zones is difficult to maintain, the engine switches to operate at the low load zone, consuming less fuel with higher system efficiency, regardless of low engine efficiency. The more efficient electric motor kept high system efficiency. This shift of engine operation points also leads to reduced emission, as shown in Figure 45, Figure 46 and Figure 47. The engine operates in a high hydrocarbon (HC) area when the electric motor contributes most of the propulsion power, but the amount of HC emission is low. This EMS also curbs CO and NO_x emission as the majority of the engine operation points are shifted to the more efficient zone.

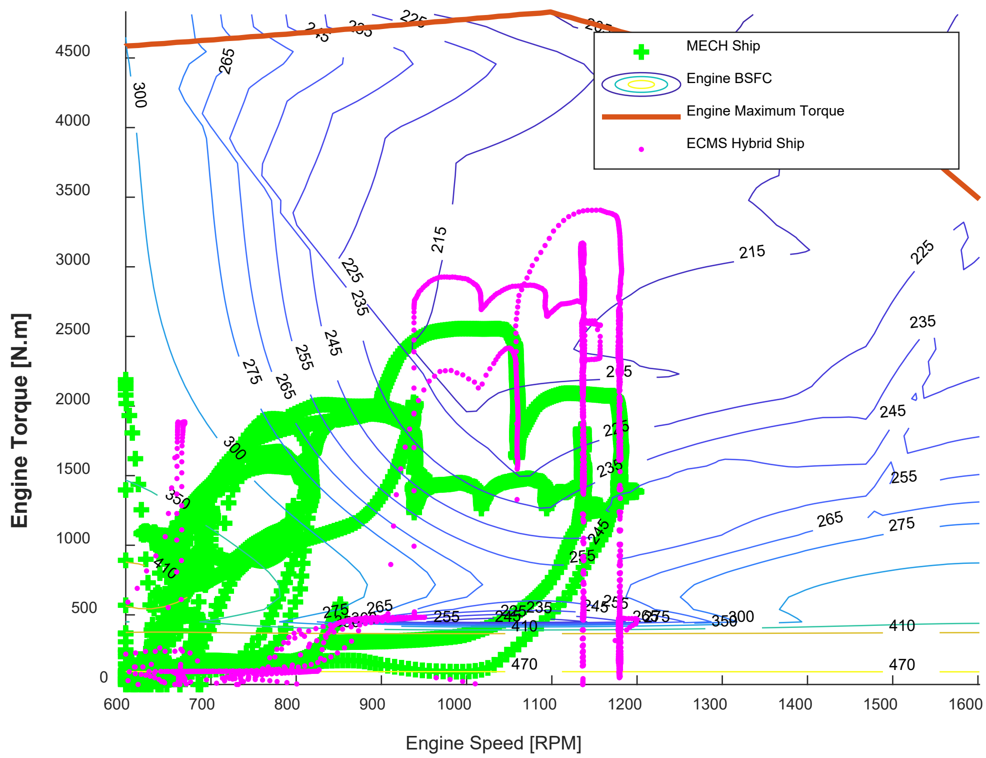

Figure 42 Engine 1 BSFC Map and Operation Points

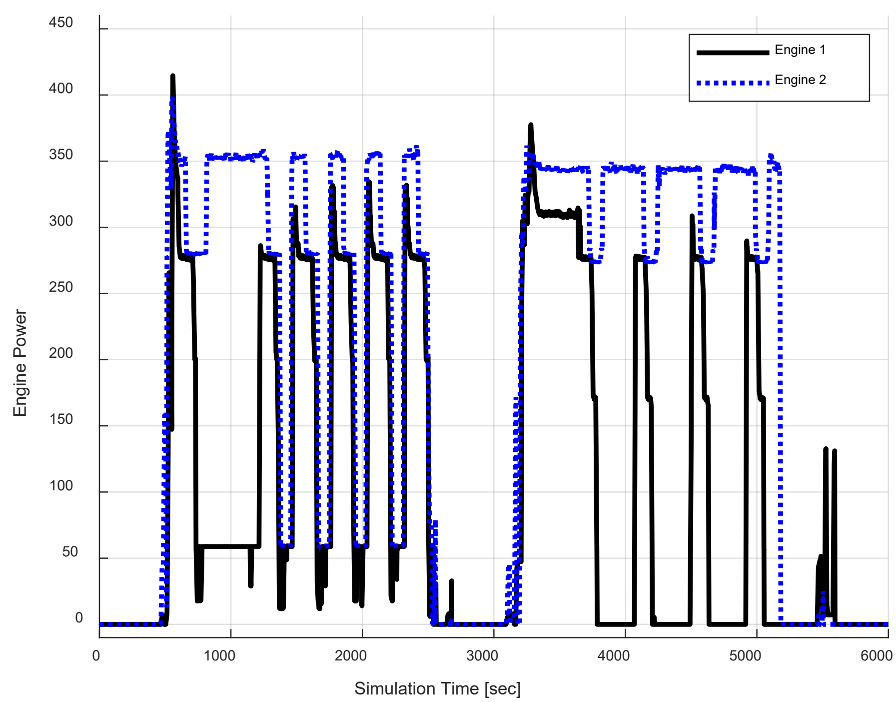

Figure 43 Engines' Power

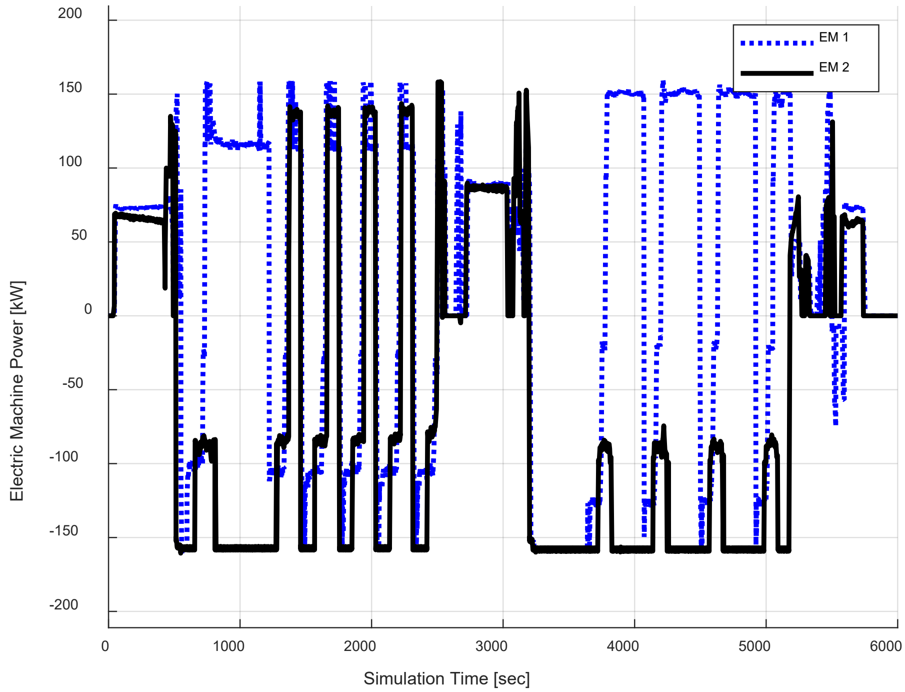

Figure 44 Electric Machines' Power

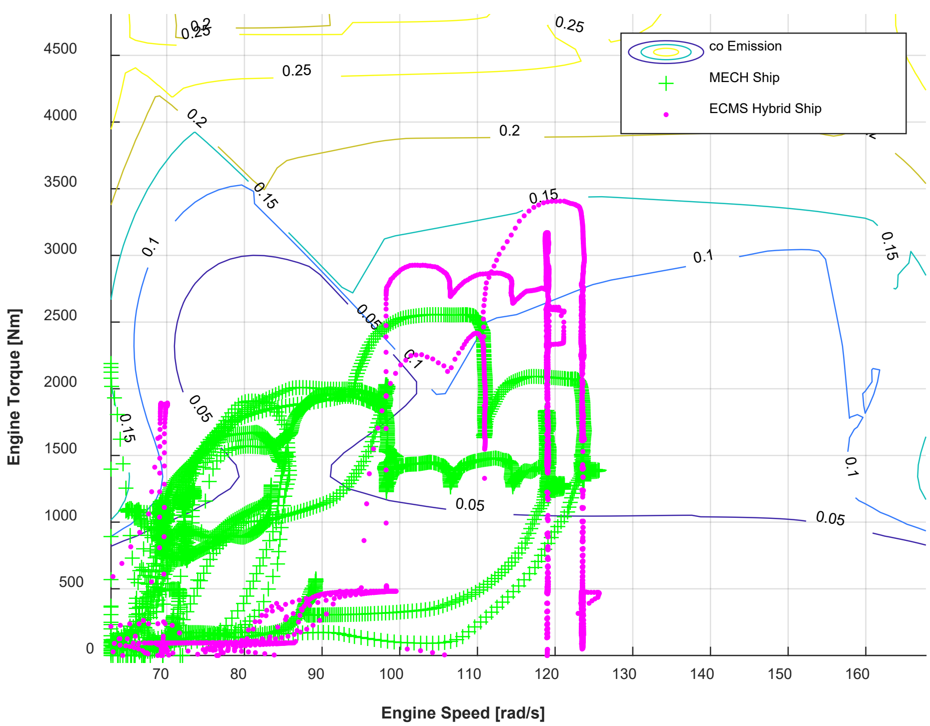

Figure 45 Engine 1 CO Maps and Operation Points

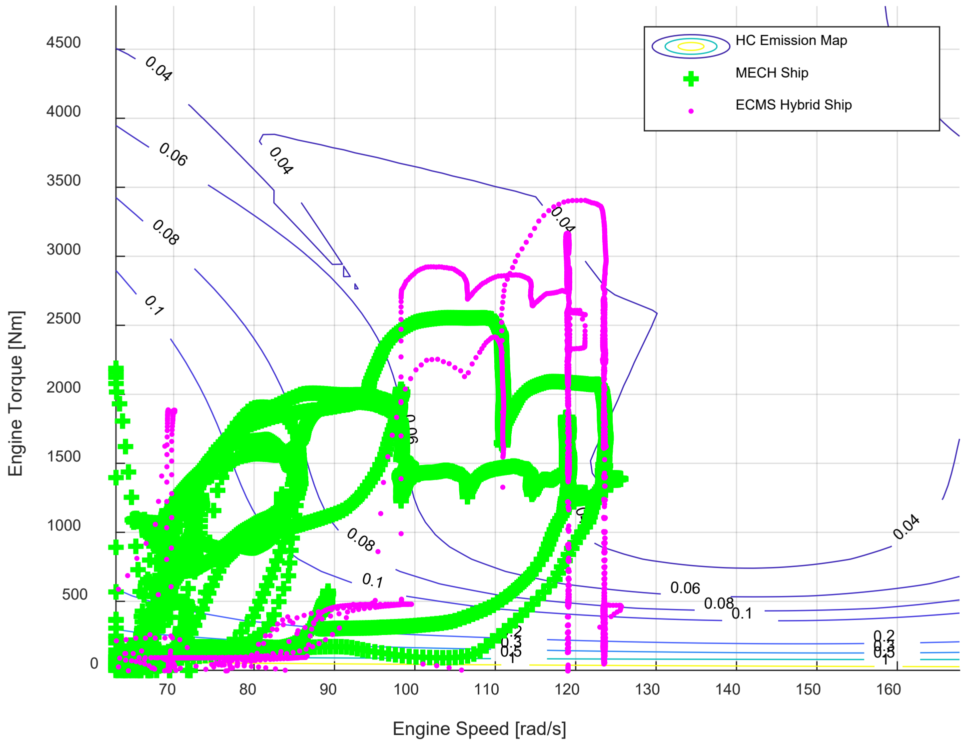

Figure 46 Engine 1 HC Maps and Operation Points

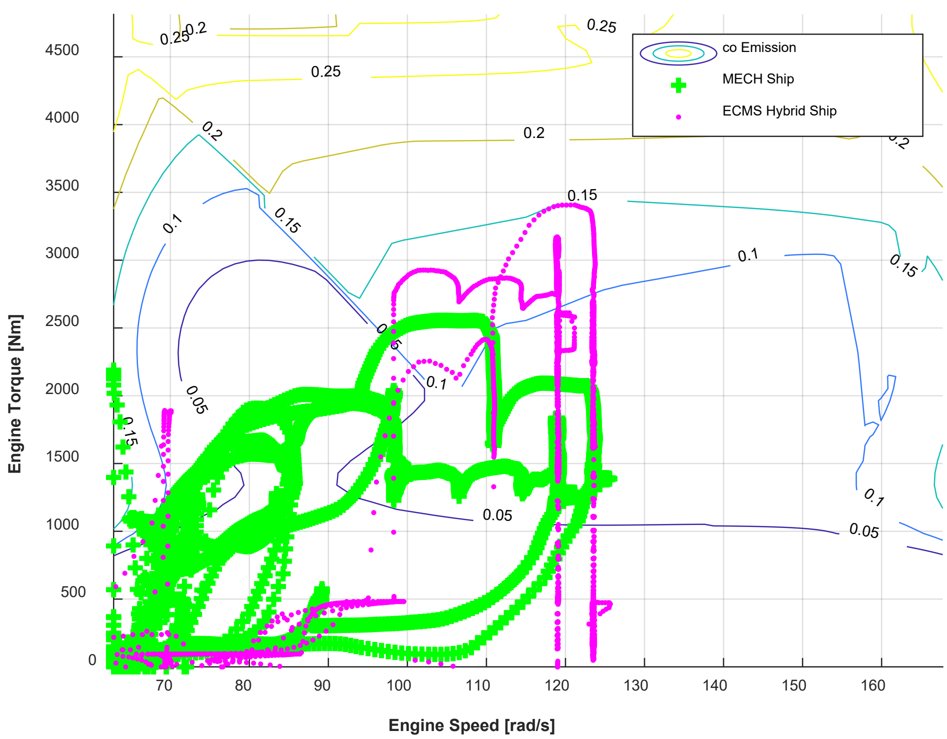

Figure 47 Engine 1 Emission Maps and Operation Points

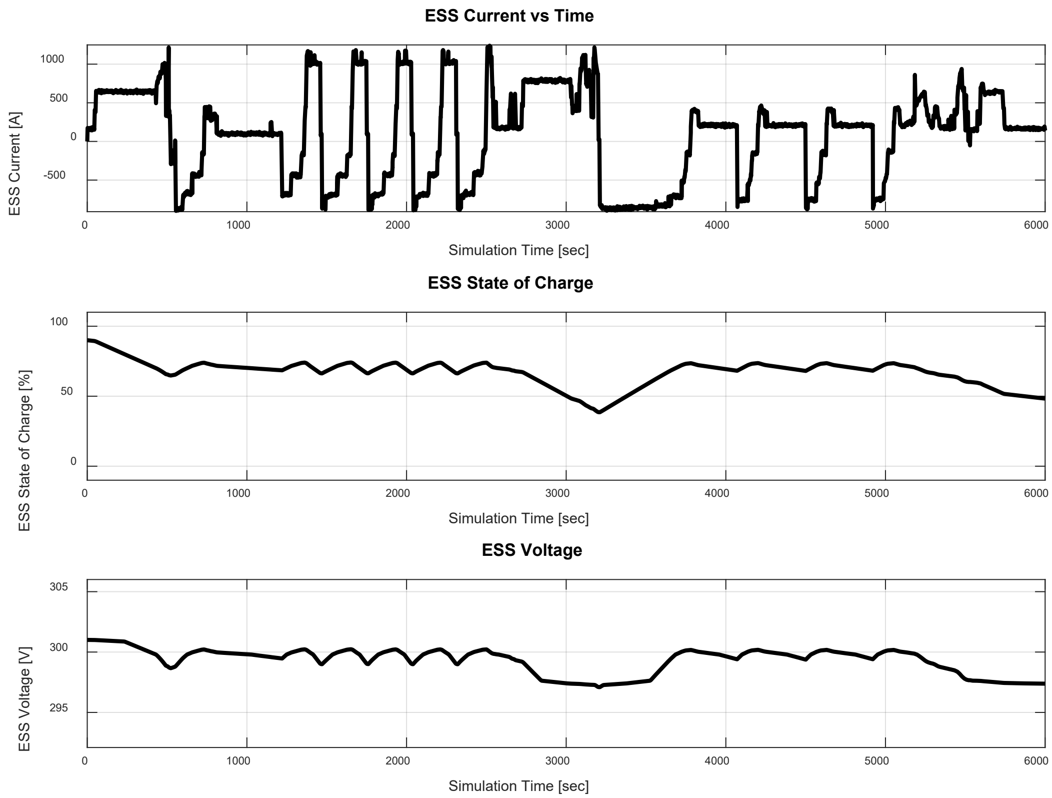

Figure 48 ESS Operation Condition

4.4. Comparison of the Simulation Results

This subsection compares the simulation results and illustrates the pros and cons of different EMSs. As discussed previously, both EMSs significantly improve the fuel economy, curb emissions, and reduce the engine operating time. Figure 49, Figure 50, and Figure 51 show the improvement of fuel consumption and emissions of the diesel-electric ship, PTO hybrid electric ship, diesel-electric ship, RB hybrid electric ship, ECMS hybrid electric ship over the conventional diesel-mechanical ship. The configuration of the MV Tachek and the diesel-electric ship is presented in Figure 19 and Figure 4.

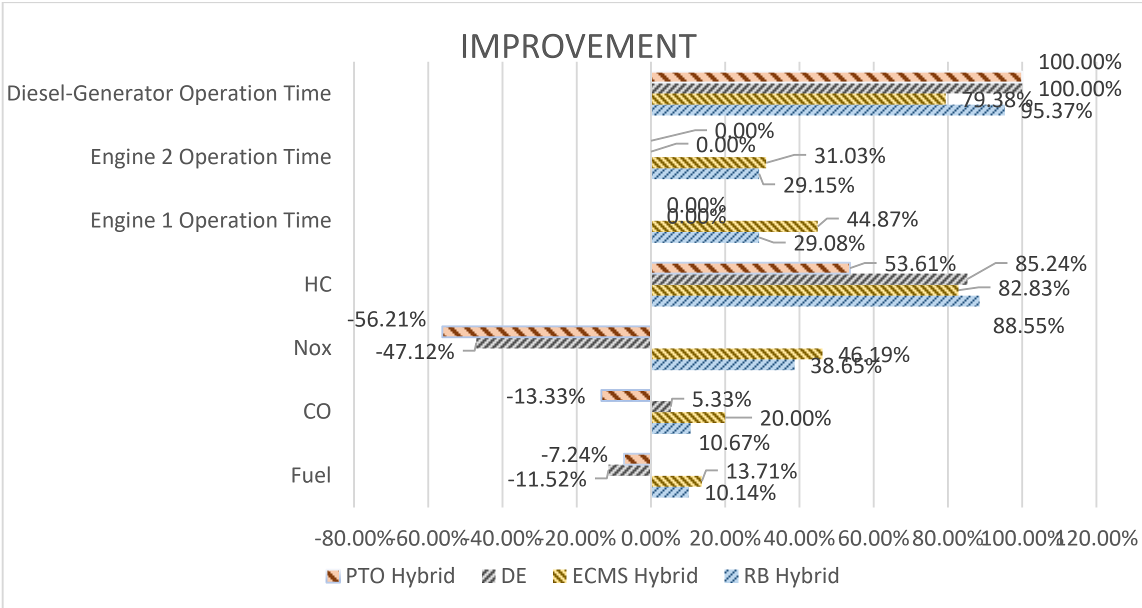

Figure 49 Improvement Compared to Baseline

This study indicates that the proposed hybrid electric ships (Rule-based and ECMS-based hybrid electric ships) significantly improve the overall fuel economy and emission. The diesel-electric ships also provide some improvement; however, there is significant energy conversion losses (from the fossil fuel, fuel convertor, generator, convertor/invertor/transformer, motor, and, finally, the propeller) [38], [39]. But the significant advantages of using diesel-electric systems are that they reduce the system cost while providing more features, such as a larger payload, less noise, and vibration, provide greater redundancy, fewer emissions, etc. The fuel consumption of the diesel-electric ship is about 12% higher than that of the conventional ship (baseline) as expected. It also produces more NO_X as it operates mainly ins the high load zone as only one prime mover is used during the operation, while two or three prime movers are used in other cases.

The PTO hybrid electric hybrid ship (Latest MV Tachek) has many degrees of freedom (DoF) in operation, rather than a single DoF as the conventional diesel-mechanical and diesel-electric drive, and relies on the controller to coordinate the operation of the engines. The simulation result showed that the MV Tachek with part-time hybridization does not save much fuel, compared to the mechanically propelled vessel. The engine operation points, shown in Figure 37 and Figure 42, are primarily located in the low-load zone, indicating low fuel efficiency and high emissions for the baseline mechanically propelled ship and the MV Tachek.

During the life-extension overhaul, two larger engines were installed on Tachek, which led to worse fuel efficiency. To meet the ship's service speed, a total propulsion power of 600 kW is enough; however, the MV Tachek has a full engine power of 1,840 kW at 1,200 RPM. The two larger engines now operate at even lower fuel efficiency bands than the original mechanically propelled ship with smaller engines.

As for fuel consumption, the ECMS-based hybrid architecture performs the best, mainly due to the advanced optimization-based EMS. The diesel-electric system suffers more energy loss during the conversion, and conventional mechanic ships are expensive to operate but are efficient [38]. The presented hybrid architecture takes advantage of both architectures and integrates with an intelligent controller, which decides the power split ratio and the operation mode for each propulsion system. ECMS-based EMS performs better on fuel economy than rule-based EMS, as it takes the ESS's efficiency and electric machines' efficiency into account apart from the engine's efficiency (as in RB); thus, the overall system efficiency is the highest. The rule-based EMS only focuses on the engine's efficiency; therefore, the RB EMS improves the overall engine operation efficiency, which produces the most significant emission reduction. Both hybrid architectures smooth out the fluctuation of engines' operation, as shown in Figure 45 and Figure 36.

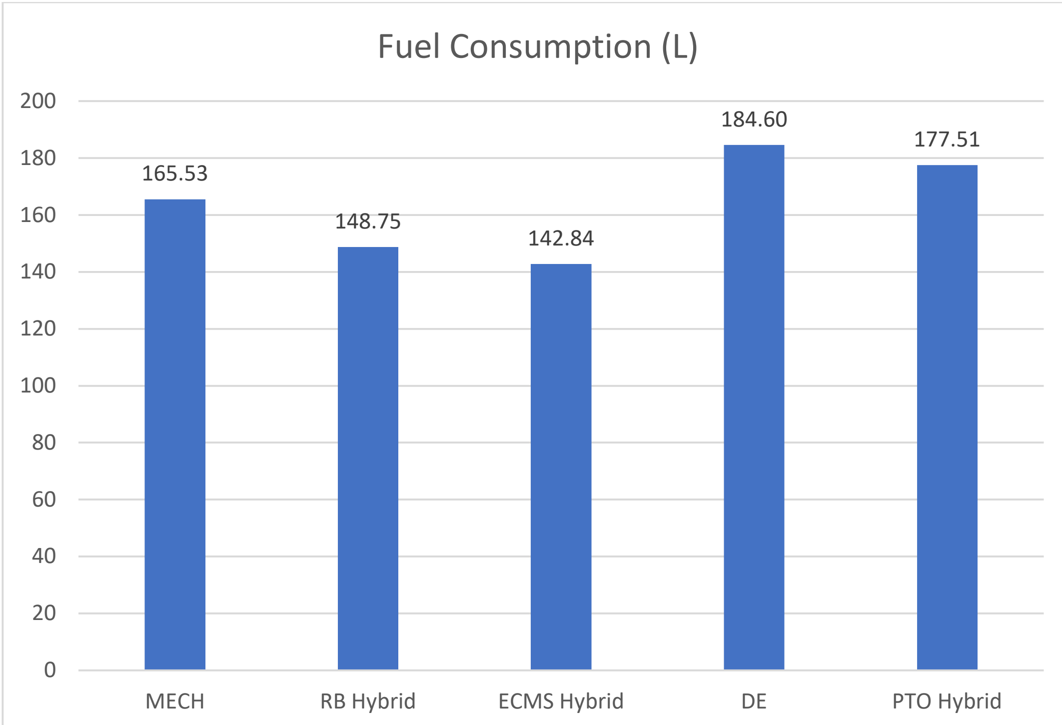

Figure 50 Compare Fuel Consumption Among all Configuration and EMSs

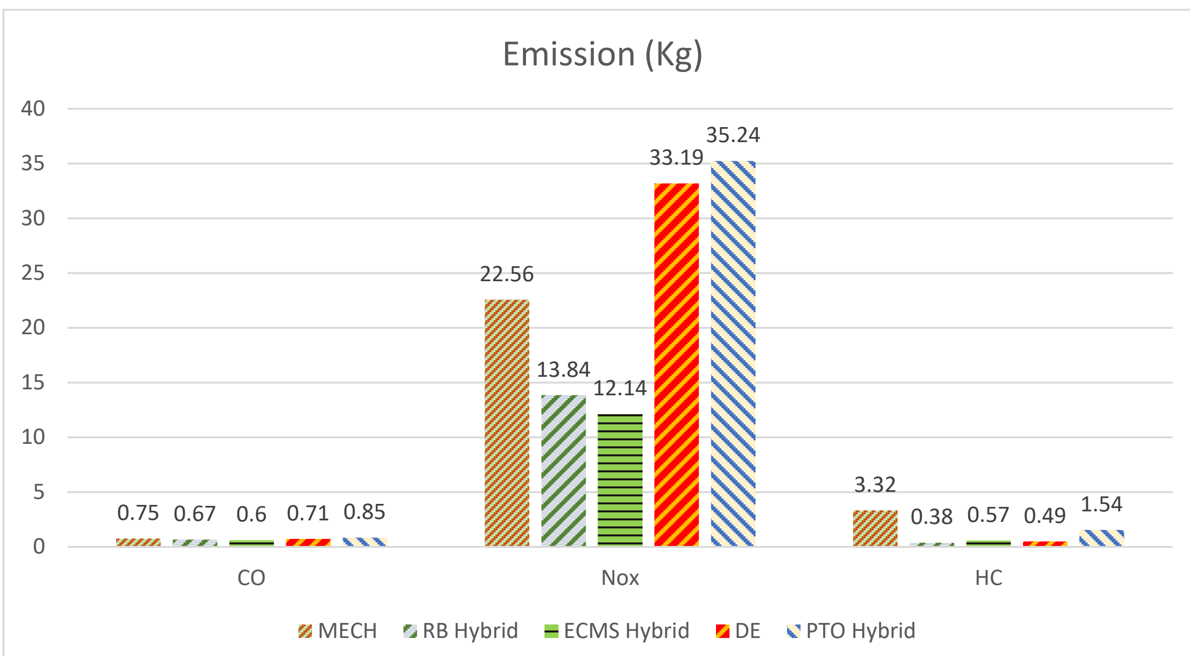

Figure 51 Compare Emission Among All Configuration and Controllers

Chapter 5 OPTIMIZATION OF HYBRID POWERTRAIN SYSTEM

The simulation platform and controller are modelled following MBD. An optimal solution is achieved on the selected components after applying the proposed power control and energy management strategy. An optimization algorithm is used to calibrate the control parameters of the propulsion system. The control parameters are optimized by applying the global optimization algorithm searching the design spaces in Chapter 4. The result shows that with the optimized parameters, the ECMS based controller achieves more fuel-saving than a rule-based controller does. The overall hybrid propulsion system is not yet optimized.

The hybrid electric propulsion system optimization includes two areas in this work: key component sizing and control parameters calibration. The architecture and modelling of the hybrid propulsion system have been introduced in Chapter 2, and the energy management strategy is introduced in Chapter 4. The goal of this chapter is to solve the optimal design problem and to calibrate the control parameters to achieve better fuel consumption while meeting the same propulsion power demand.

This chapter is devoted to:

a) Defining the optimization problem.
b) Addressing the optimal design and optimal control challenges: and developing the optimization-based energy management controller and sizing components.
c) Introducing the optimization method and the application, and
d) Concluding the studied case.

5.1. Problem Formulation

A number of papers on land vehicle applications [40] mentioned that increasing the level of vehicle hybridization would lead to more emission reduction as more electric propulsion capability is added since the purely electric mode is prolonged with a sufficiently large ESS. However, the associated cost increases significantly. The same principle also applies here in marine applications. The benefits and drawbacks of a pure electric ship have been discussed in numbers of papers, thus will not be assessed in this chapter. From an engineering perspective, a ship equipped with an over-designed engine always holds the goal of improving the system efficiency back and produce more emission then a propel designed ship, as the engine always operates at a low-efficiency zone. As a consequence, solving this optimal design problem plays an important role in reducing fuel consumption. What complicates the issue is that as more power and energy sources are integrated into the system, the supervisory controller that significantly affects the system performance becomes much more complicated. The commonly used design optimization methods become extremely inefficient in solving a complex optimization problem that involves a system that contains the mechanical system, electric system and embedded controllers. The resulting system performance behaves differently, demanding advanced system controls [17], [41]–[44].

Overall, the calibration process of the controller is not neglectable when finding the optimal components for the given operation task.

The system model is constructed using Matlab/Simulink as introduced in previous chapters. The optimization problem can be defined as:

$$f_{obj} = f(P_{eng}, P_{EM}, S_{factor}) \quad (5\text{-}1)$$

where P_{eng} represents the engine rated power, P_{EM} denotes the electric machine continuous maximum power, S_{factor} are the equivalent factors introduced in Chapter 4 with two parameters, the positive power conversion efficiency (motor power conversion efficiency) and negative power conversion efficiency (generator power conversion efficiency). Both parameters have the same boundary conditions in this setup.

The predefined ship operation profile is used as an input to evaluate the ship's performance. The ESS energy consumption is not neglectable as the ESS SOC may not be the same as the final SOC once the operation task is finished and may vary under different configurations, different EMSs, or control parameters. The same method is used to evaluate the electric power consumption and convert those energies into fossil fuel as introduced in Chapter 4. Fuel economy is used to evaluate the performance, as shown in Equation (5-2). The f_{diesel} denotes the total fossil fuel consumption for all the diesel engines; Function f_{ess} calculates the fuel consumption of diesel generators, which is used to charge the ESS to the initial value after each operation. This block returns a vector that contains the diesel generator operation time, fuel consumption and emissions. ΔE_{ess} is the electric energy (at the final state) that differs from the initial ESS energy. The sum of the above represents the total equivalent fuel consumption, which is used to evaluate the performance.

$$f_{all} = f_{diesel} + f_{ess}(\Delta E_{ess}) \tag{5-2}$$

Table 13 Component Sizing Parameters and EMS Calibration Parameters

Parameter	Engine Power	EM Power	ECMS Factors, S_b
Range	[460, 1060]	[60, 690]	[0,10]

Thus, the formulation can be summarized, and the optimization problem can be deduced as below:

$$\min f_{all}(P_{eng}, P_{EM}, S_{pos}, S_{neg})$$

subject to:

$$P_{min} \leq P \leq P_{max}$$
$$0 \leq SOC \leq 1 \tag{5-3}$$

where P_{max} and P_{min} represent the corresponding max/min power at specified operation conditions for EMs, engines, ESS, etc... SOC is limited as there is a safety concern. Apart from that, overcharging and completely draining the battery will affect the battery life significantly. The engine's size, EM's size, and the boundary of the controller parameters are presented in Table 13.

5.2. Components sizing using Bi-level Nested Multi-start Space Reduction (MSSR) surrogate-based global optimization method

Due to the complexity of this problem, some parameters are more sensitive than others, which makes a general the global optimization method trapped in a local minimum easily.

While tuning optimal controller and powertrain configuration together, the hybrid system behaving differently under varying conditions, determined by different component sizes, control parameters, and architecture. The generic global optimization algorithm can solve an optimal design problem and calibrating the optimal control parameters separately. However, it is not useful in solving an optimization problem with the complex multiphysics system that contains the mechatronic and embedded systems. The algorithm is very likely to be trapped at a local minimum, sometimes even failed to find the optimal solution.

The complex optimization problem, with interrelated system design and control development for minimizing fuel consumption, is solved using a metal-model global optimization algorithm. The optimization process consists of two parts. The bottom level search focuses on calibrating the control parameters for the giving powertrain components, while the top-level search focuses on finding the optimal powertrain component sizes. The integrated design and control optimization method, shown in Figure 52, is a computationally intensive, black-box global optimization problem.

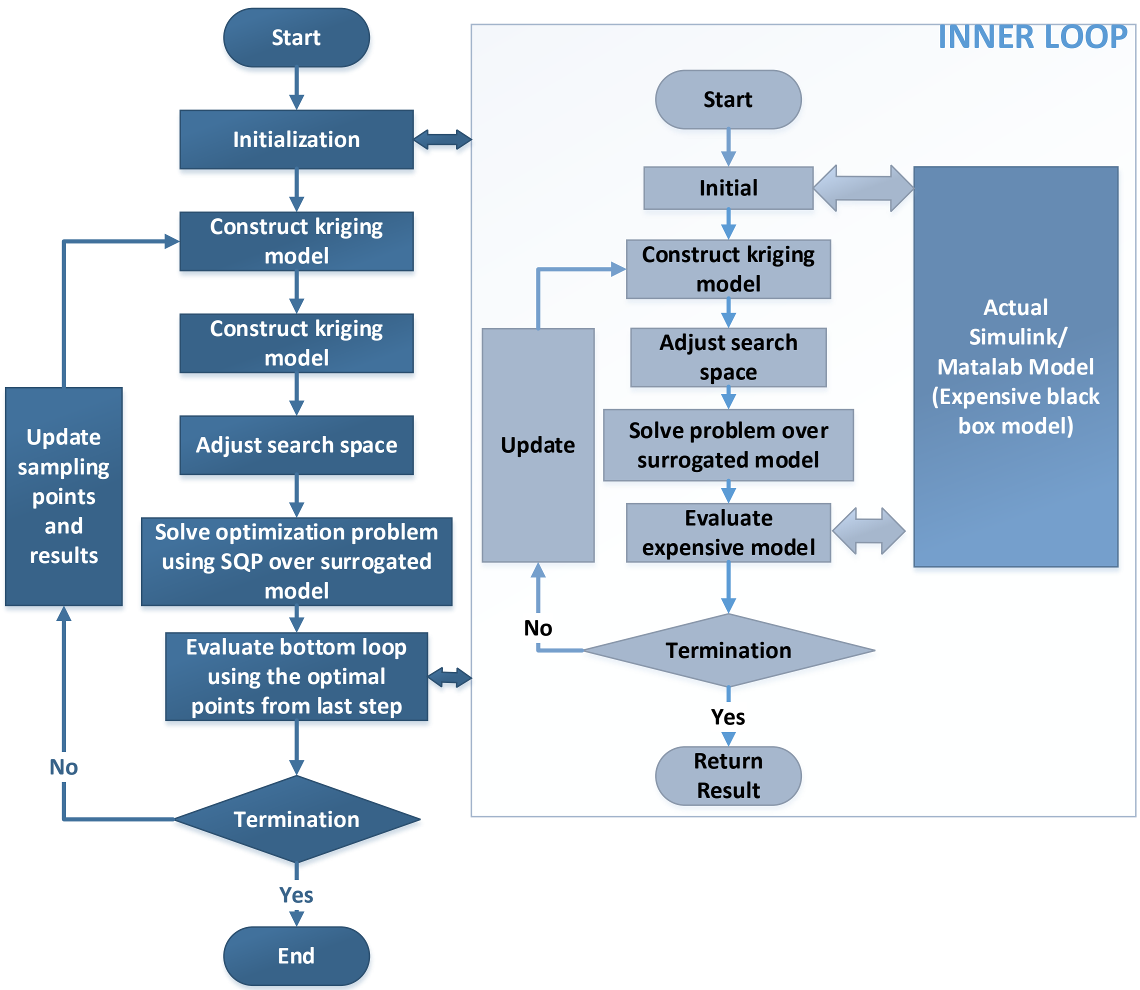

Figure 52 Nest Optimization Framework

The goal of top-level optimization is to solve the fuel minimization problem with regard to the given components sizing. Typically, by reducing the engine size, the ship will consume less fuel under the same load demand but reduce reserved capability. Increasing the electric machine power will decrease the EM efficiency under the same operating conditions. Still, a small EM may not be capable of operating in pure electric mode or provide sufficient power in motor assistant mode. Therefore, the optimization process needs to find the balance at the system level and let the bottom level deal with the optimal control calibration problem. The objective function of the top-level can be summarized as in Equation (5-4), and this turns the top-level component sizing optimization problem into an unconstraint problem:

$$\min f_{outer}(P_{eng}, P_{EM}) \tag{5-4}$$

The goal of bottom-level optimization is to calibrate the control parameters under given component sizing. The inner loop object function can be reformed as in Equation (5-5):

$$\min f_{inner}(S_{pos}, S_{neg})$$

$$\text{subject to} \quad P_{min} \leq P \leq P_{max} \tag{5-5}$$

$$0 \leq SOC \leq 1$$

The goal of the bottom-level optimization is to minimize fuel consumption, to meet all control constraints, and to utilize the flexibility of the hybrid powertrain fully. The top-level aim to solve an optimal design problem that minimizes fuel consumption. All those forms a nested computationally intensive global optimization problem due to evaluating the inner loop frequently, which is already an expensive controller calibration problem. Questions have been raised on prolonged computation time for deducing the optimal design and control result using conventional global optimization algorithms, such as Generic Algorithm (GA), Particle Swarm Optimization Algorithm (PSO), Grey Wolf Optimization Algorithm (GWO), etc. Thus, a highly efficient metamodel-based optimization algorithm named Multi-Start Space Reduction (MSSR), developed by Dong *et al.* [45], is used to solve this computational expensive optimization problem in both inner loop and outer loop.

This MSSR algorithm uses a multi-start approach to the Kriging-based optimization method. MSSR reduces the model complexity by searching over the generated surrogate models instead of searching global space in the original complicate model and focusing on exploring various feasible regimes where the global optimum may exist. The surrogate model is generated using Kriging Toolbox and fitted the mathematical function to expensive object function, which requires a large amount of computational capacity. The algorithm searches alternating original design space, reduced medium space, and local space. Latin hypercube sampling and sequential quadrat programming (SQP) is used to select and explore new and better points and solving the local optimization problem. Next, those local optimu is evaluated using the expensive model.

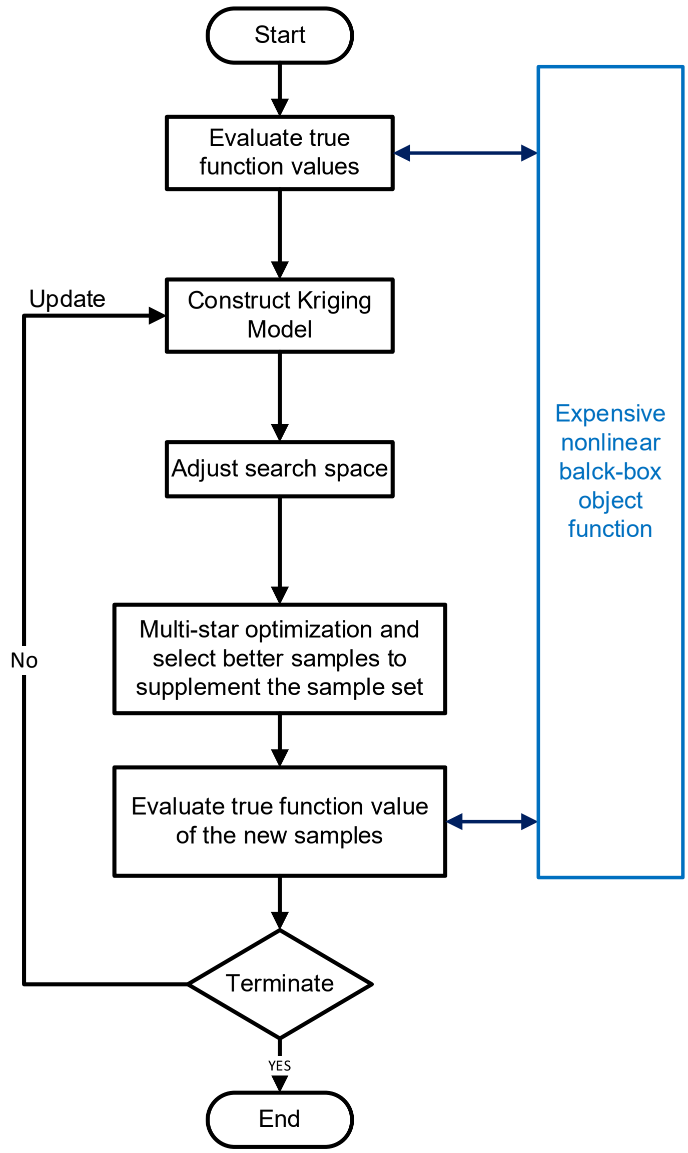

Figure 53 MSSR Flow Chart [45]

The process of MSSR can be summarized below:

a) Initialize the algorithm, evaluate points generated by Latin hypercube sampling and rank all the results.
b) Construct the Kriging model upon simulation.
c) Adjust the search space.
d) Select sampling points, explore new points and unknown areas.
e) Evaluate the true object function (and model) using the sampling points generated in step d.

f) Update the simulation result and construct a new Kriging model (go to step b).

The MSSR algorithm keeps searching until the termination criterion is triggered, such as the maximum iteration count is reached.

The main reason for choosing MSSR is its high searching efficiency. For an engineering optimization application, a closed-form expression is hard to obtain. A common approach is to use stochastic optimization methods. However, this requires an intensive evaluation of expensive objective functions. By adopting a meta-modeling optimization method, a surrogate model is generated based on a few function evaluations over the expensive original objective function. Next, a local optimum is obtained by applying a conventional optimization algorithm over the surrogate model. Only the locally optimal solution is evaluated in the computational expensive objective function. As presented in Table 14, comparing the number of function evaluations (NFE) and accuracy, the MSSR performs best in all tested on the notorious banana function [45]. The banana function is famous for its slow convergence most optimization algorithms exhibit when trying to solve this problem and is one of the widely used benchmark test cases in the global optimization method. The author did not compare MSSR to conventional global optimization algorithms, but in [46], Jiajun Liu of our team has compared the performance among GA and MSSR on an energy minimization problem of a hybrid electric load-haul-dump (LHD) vehicle equipped with a hybrid energy storage system (HESS). Both algorithms convergence after a few iterations, however, MSSR achieves a better result (15.92% better than GA) with fewer function evaluations (63.33% less than GA). Overall, this method emitted the needs of evaluating the sampling points over expensive black-box objective function and could accelerate the optimization, and the simulation time is reduced from few months (when using conventional stochastic optimization algorithm) to 15 days in this study.

Table 14 Preliminary comparison results on Banana functions [45]

Algorithm	Harmony Search	Differential Evolution	DIRECT	MPS	EGO	MSSR
NFE	9122	190	603	145	216	41
Min	8.84e-4	4.05e-4	3.01e-4	0.0358	9.67e-4	3.45e-4

5.3. Simulation Results

This subsection analyses the simulation result, which is implemented using the proposed method. The hybrid propulsion systems were created using the techniques presented in Chapter 2, Chapter 3 and Chapter 4 in MATLAB/Simulink. The nest optimization codes were developed in MATLAB, and parallel computing [47] is used to achieve the full power of a multicore computer to significantly reduce computation time.

The optimization identified the optimal component sizes, and the optimized design performed best among all simulated alternative designs. Figure 54 shows the engine 1 operation points, and Figure 55 and Figure 56 present the power split between the engine and the electric machine. In this configuration, the electric machine is capable of operating in motor mode (or all-electric mode) in all conditions. The operation pattern differs from the architecture proposed in Chapter 4 with smaller EMs. The EM plays a more significant role in this configuration, as the system tends to operate in motor mode. Figure 57 shows the ESS current, voltage, and SOC during the simulation. The SOC is maintained in the desired range. However, due to the cyclical operation patten, ESS current is significantly larger than the ECMS hybrid and RB hybrid in Chapter 4.

Compared to baseline, the optimal ECMS hybrid ship saves fuel by 17.4%. And a 3.7% improvement over ECMS hybrid electric ship (introduced in Chapter 4). In this setup, the engine operation efficiency is not maximized, but the higher system efficiency provides more fuel-saving than other configurations. The system tends to operate at a high load zone and charge the ESS, turn off engines or operate the engine at a low load zone. The system switches between pure electric mode and peak shaving mode and turns on/off engines in a cyclical manner. This ship significantly improves system efficiency.

Table 15 Simulation Result for Optimal Hybrid Ship

	Base Line	ECMS Hybrid	Optimal ECMS Hybrid
Fuel Consumption	165.5 L	142.8 L	136.7 Kg
CO	0.8 Kg	0.6 Kg	0.9 Kg
NO_x	22.6 Kg	12.1 Kg	5.0 Kg
HC	3.3Kg	0.6 Kg	0.2 Kg
Engine ON Time	6000 / 6000 / 6000	3308 / 4138 / 1237	2339 / 2405 / 1436

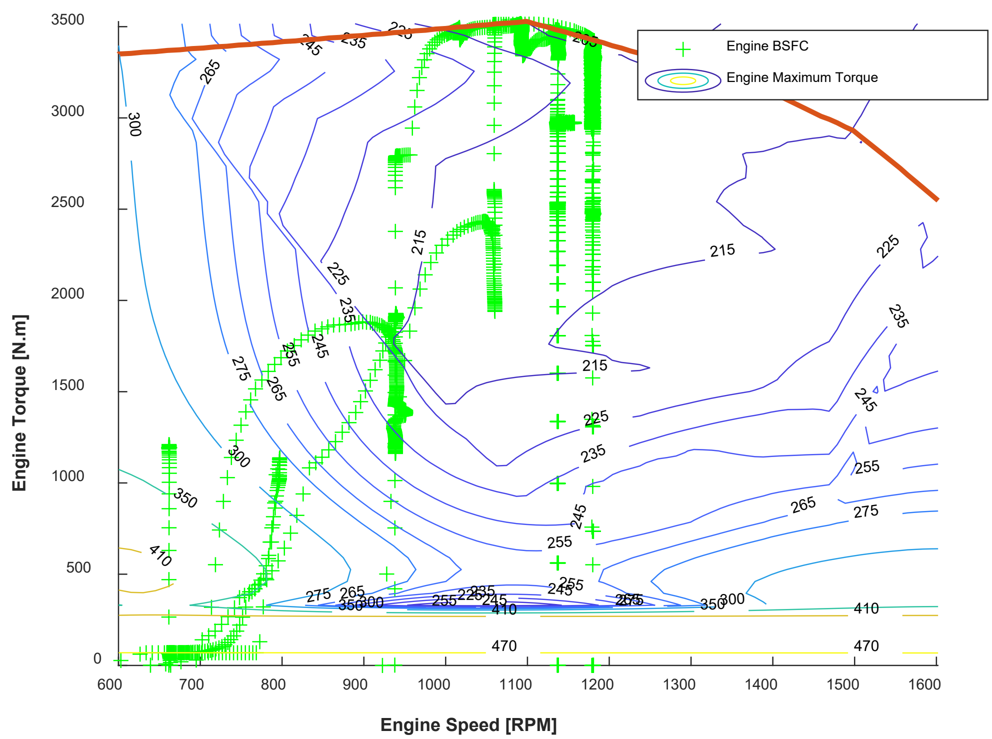

Figure 54 Engine 1 Operation Points

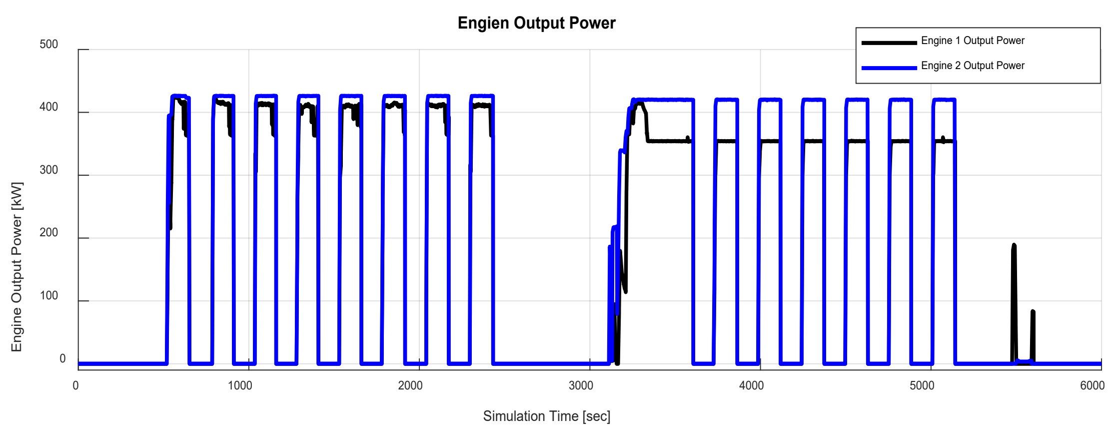

Figure 55 Engines' Power

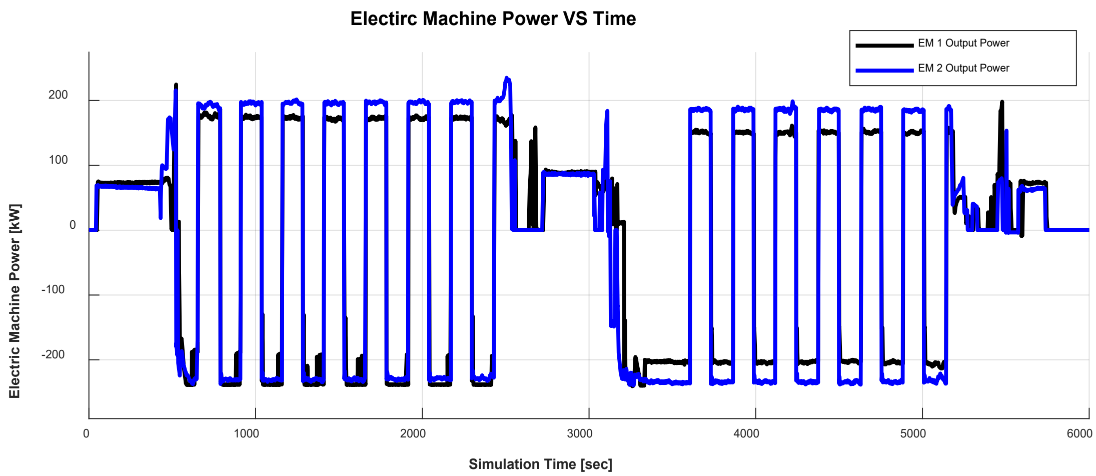

Figure 56 Electric Machines' Power

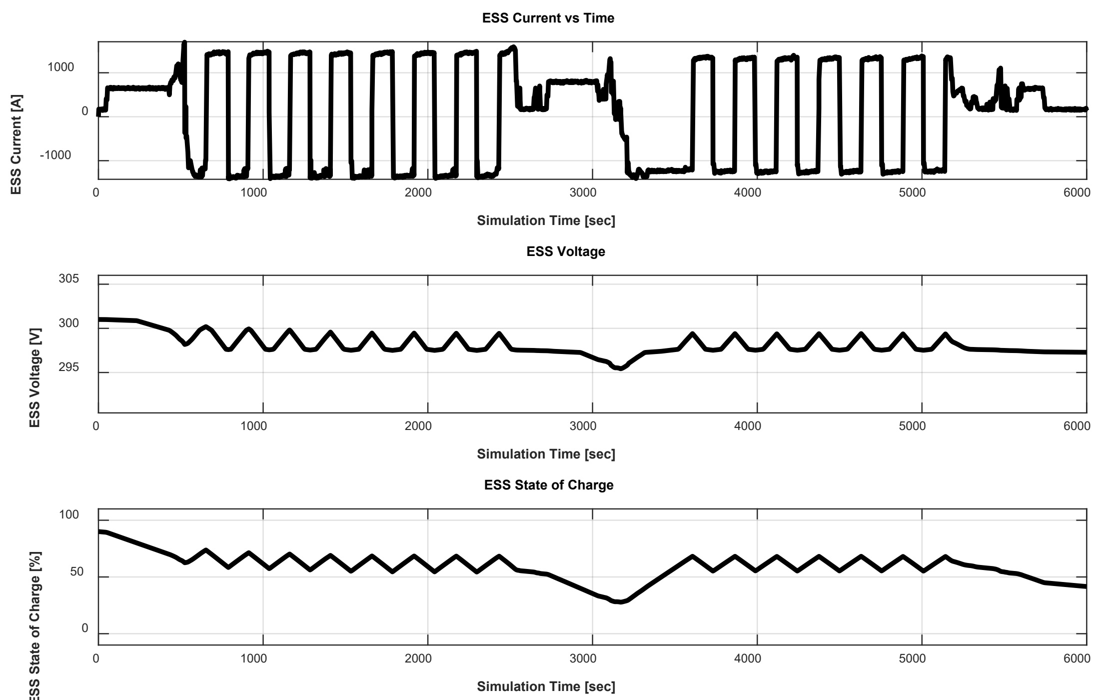

Figure 57 ESS Current, SOC and Voltage

The presented nested optimization framework performances is able to find the global optimal solution, and fuel consumption has a significant improvement compared to the findings in Chapter 4. Figure 58 shows the optimal fuel consumption at each searched design space (top-level). Figure 59 presents the inner loop searching process for selected component size and Figure 60 presents the searching process for the optimism design. The result shows that the MSSR searching efficiency is relatively high, the optimization converges in only a few iterations, and only it requires few function evaluations to attain the optimal control parameters. The searching process is robust as most of inner loop searching processes merge to the corresponding optimal solution in only a few interactions as shown in Figure 59 and Figure 60.

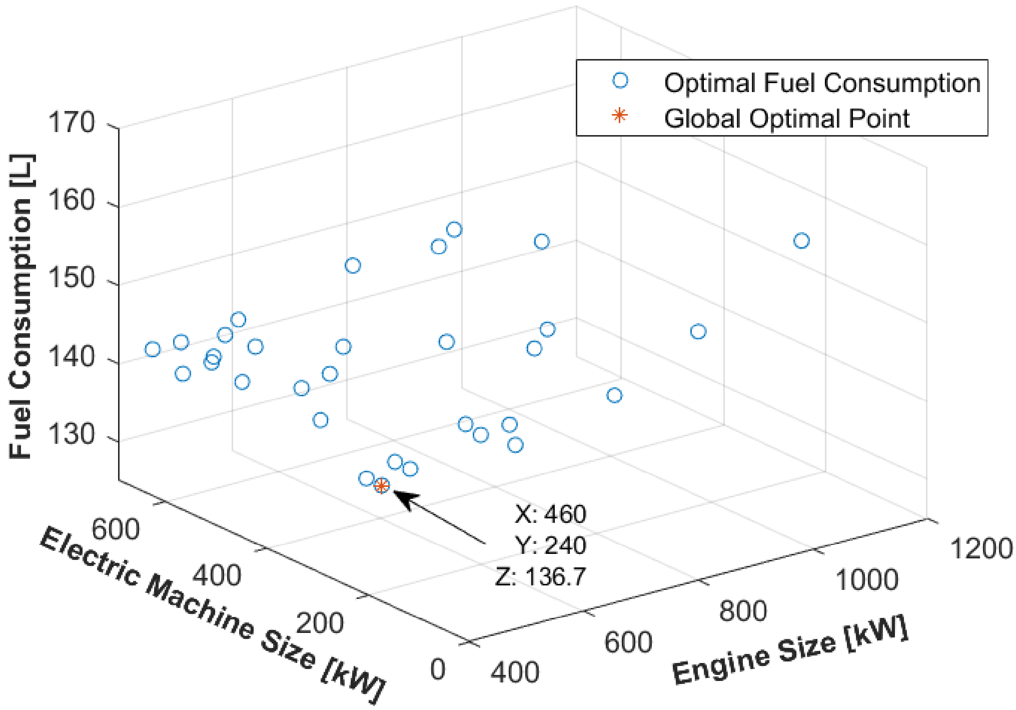

Figure 58 Top Level Sampling Points and Result

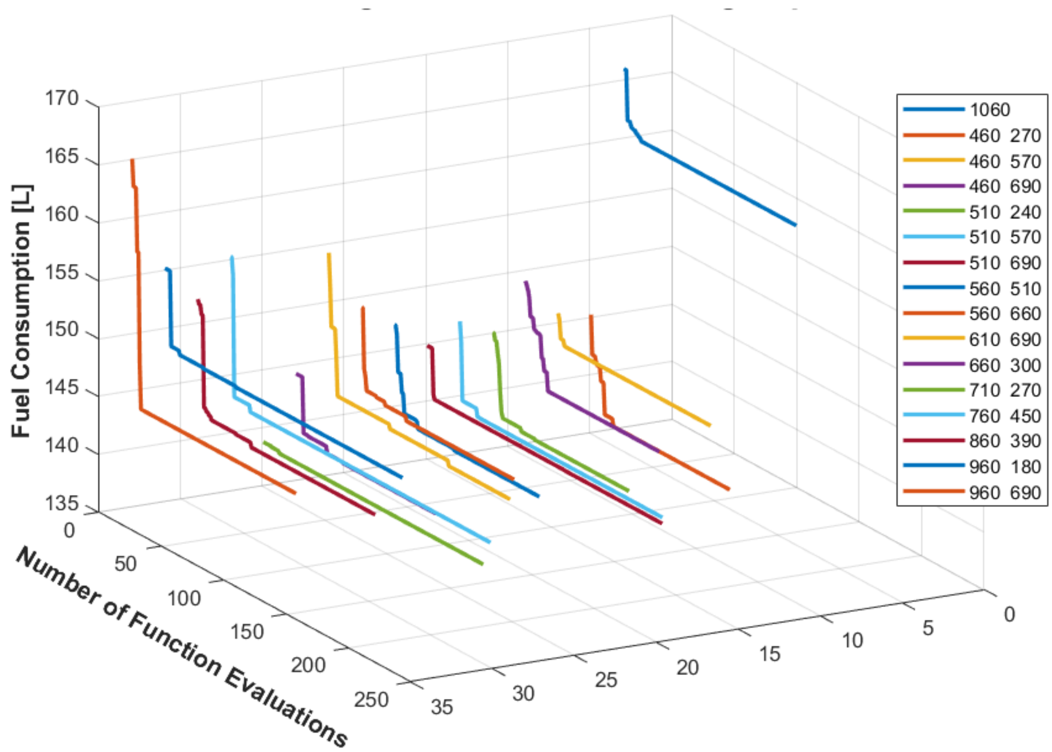

Figure 59 MSSR Inner Loop Searching Process (Multi-Component Sizes)

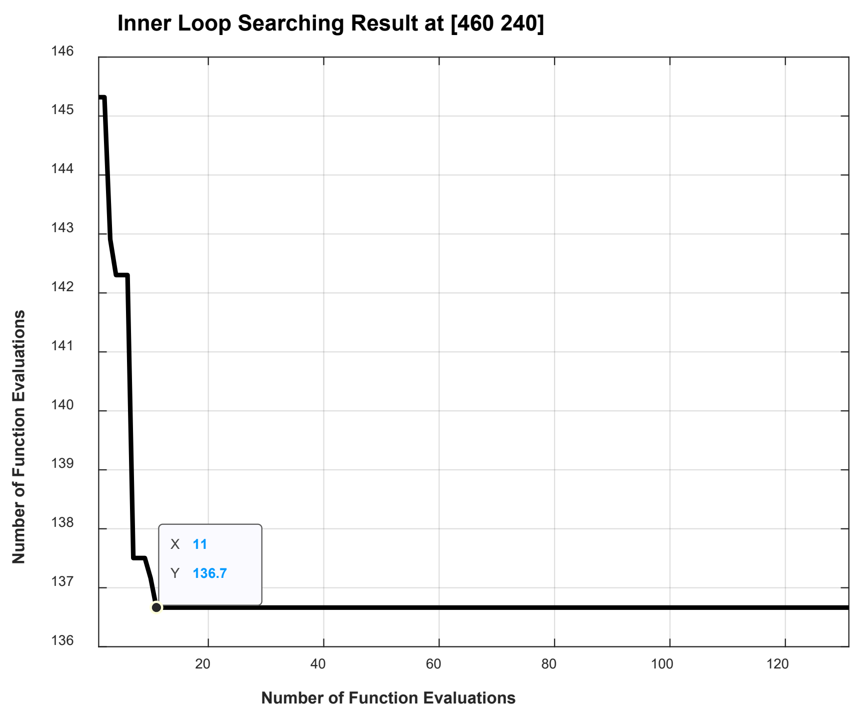

Figure 60 Inner Loop Searching Process at Global Optimal Sampling Points

Chapter 6 Conclusion and Outlook

In this research, the modelling, design and energy management of a hybrid electric ship have been studied. The new integrated, model-based design and optimization methods have been presented and applied to the case study on one of BC Ferries vessel, MV Tachek.

The operation profile of the ship is first established to serve as the design inputs and the model validation data of this work. The systematic methodology for solving the introduced optimal design and control problems of the hybrid electric marine propulsion system has been discussed in detail. The conventional diesel-mechanical drive ship is modelled as the benchmark case study, and a PTO/PTI hybrid electric powertrain architecture is introduced. Rule-based and optimization-based energy management strategies are introduced and applied to the benchmark ship and the newly proposed hybrid electric ship with real-time EMS aimed at minimizing fuel consumption and CO_2 emissions. In the rule-based EMS, the essence of the control strategy is to ensure that the engines operate efficiently at the highly efficient speed and torque zone with maximum fuel efficiency, due to their "dominant position." The optimization-based EMS, on the other hand, focuses on minimizing the equivalent fuel consumption (or equivalent energy usage) in each time step, in which the fuel rate, electric energy consumption, and energy loss are taken into account. This design optimization and optimal control study forms the foundation for further research and provides more insight into the intricate design and control issues of hybrid electric marine propulsion, as well as the relationships among different functional components of the electrified and hybridized marine propulsion systems.

6.1. Research Contributions

In this work, the modelling platform, design optimization and optimal control method for a hybrid marine propulsion system have been introduced and presented. The research is aimed at introducing the new methods for developing an energy-efficient marine vessel using the introduced methodology and research platform, and for searching the optimal design and control solutions using the newly introduced nested optimization approach. Detail research contributions include:

- Collected ship operation data and built the operation profile model for the vehicle and passenger ferry MV Tachek from BC Ferries.

  A ship operation profile is needed to define the power and operation requirements for operating a marine vessel. Due to the wide diversity of hull geometry, propulsor type, load, ocean conditions on the sailing route, and a small batch of vessel production, the vessel operation profile is case dependent, and no accurate generic vessel operation profile is available to guide the design and control development of marine propulsion. As a large part of the research effort to build the operation profiles for most commonly used marine vessels in Canada, this thesis presented the method for build the operation profile using various ship operation data using MV Tachek as an example. The ship operation data were acquired from the ship propulsion power (propeller seed and torque) measuring and data recording apparatus, ship voyage data recorder (VDR), and the technical documents of the ship (stability book and operation logbooks). These data collected from the MV Tachek are processed to form the operation profile of the vessel.

- Introduced a modelling platform using the Model-Based Design (MBD) approach to support the concept design and analyses of the hybrid propulsion system, and modelled four different propulsion systems using this modelling platform.

  Although the MBD methodology has been widely used in the automotive and aerospace industries, these computer models and modelling software were not available for marine applications. The new software platform developed in MATLAB/Simulink provides an efficient method for modelling and analyzing the performance, energy efficiency and emissions of different marine propulsion systems. The platform also supports the design optimization of the propulsion system and the development of optimal power control and energy management for a given propulsion application.

- Developed and tested two different power control and energy management methods, rule-based and optimization-based methods, for the selected hybrid propulsion system architecture and system components.

Both controllers improved fuel economy, reduced emission, and maintained desired SOC of the battery ESS, while meeting the propulsion power demand of the vessel.

- Carried out an in-depth study on the parallel hybrid electric propulsion system of the vessel, which imposed considerable challenges in system control and presented a potentially more efficient hybrid electric marine propulsion technique with lower energy conversion losses in relative to the straightforward and commonly-used series hybrid electric propulsion.

  Detailed control algorithms for parallel hybrid electric marine propulsion have been introduced, and the advantages of parallel propulsion have been demonstrated.

- Introduced and tested an efficient and robust method for identifying the optimal propulsion system design and controls by formulating a nested optimization problem and solving the problem using an advanced metamodel-based global optimization search algorithm.

6.2. Future Work

The hybrid electric marine propulsion can significantly reduce fuel consumption and emissions for marine vessels. However, there still exist some areas that need to be further invested:

- Only ECMS and rule-based power and energy management strategies are studied in this work. Other methods should be considered, such as the commonly used optimal control techniques for vehicles, PMP, APD, etc.
- Other types of hybridization technologies have not been evaluated in this study. Other architectures such as series hybrid architecture, power split (equipped with e-CVT [48], [49]) have not been covered in this work. Other types of energy sources such as fuel cell, solar power, and gas turbine are not evaluated in this study.
- The global optimization method, Dynamic Programming, has not been applied. The real benchmark study is missing in this work. The DP provides a unique global

optimization result which illustrates the full protentional of the proposed architecture and should be evaluated in the future.

- The longevity of the Li-ion battery was not studied. Most of the machines on board can last decades. However, the life of the battery is still unknown, as it is affected by many various aspects such as controller, operation, and the size of the ESS.
- The life cycle cost of the hybridized marine vessel was not evaluated. The pure electric ship should be the most economical in the short term. However, the added costs of replacing deteriorated batteries every few years would significantly increase the price due to the high replacement cost of the batteries. As for the hybrid ship, the capacity of ESS notably affects the operating cost and maintenance cost. When a larger ESS is chosen, the cost of building the vessel will be closer to a pure electric ship (or even higher). However, different EMS will significantly affect the battery's life and change the life cycle cost. Evaluating the life cycle cost is needed and is highly case dependent, and should be investigated in the future.
- The powerful hardware in the loop (HIL) simulation has not been applied in this study to verify the real-time optimal power control and energy management results. Traditionally, testing on the control system is not possible until the system integration is done, which may identify many issues, including the delay of the project, injuries, equipment failures, or even damages. It is also costly to build a real experiment plant. By adoption of HIL simulation [50] and Model-Based Design [51], [52], the efficiency of developing and testing new controls can be significantly improved.

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