A strategy for power management of electric hybrid marine power systems

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2019

Chua, L. W. Y. (2019). A strategy for power management of electric hybrid marine power systems. Doctoral thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/103414>

<https://doi.org/10.32657/10220/48078>

**NANYANG
TECHNOLOGICAL
UNIVERSITY**

SINGAPORE

**A STRATEGY FOR POWER MANAGEMENT OF
ELECTRIC HYBRID MARINE POWER SYSTEMS**

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**SCHOOL OF MECHANICAL AND AEROSPACE
ENGINEERING**

2019

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ELECTRIC HYBRID MARINE POWER SYSTEMS**

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SCHOOL OF MECHANICAL AND
AEROSPACE ENGINEERING

A thesis submitted to the Nanyang Technological
University in partial fulfilment of the requirement for the
degree of
Doctor of Philosophy

2019

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution.

27 March 2019

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A handwritten signature in black ink, appearing to read 'Liza', with a long vertical stroke extending downwards from the end of the signature.

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Supervisor Declaration Statement

I have reviewed the content and presentation style of this thesis and declare it is free of plagiarism and of sufficient grammatical clarity to be examined. To the best of my knowledge, the research and writing are those of the candidate except as acknowledged in the Author Attribution Statement. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

27 March 2019

Date

Tegoeh Tjahjowidodo

Authorship Attribution Statement

This thesis contains material from four paper(s) published in the following peer-reviewed journal(s) / from papers accepted at conferences in which I am listed as an author.

Chapter 4 is published as Chua, L.W.Y., Tjahjowidodo, T., Seet, G.G.L., Chan, R., and Ådnanes, A.K. (2016). “Equivalent Consumption Minimization Strategy for Hybrid All-Electric Tugboats to Optimize Fuel Savings”, *Proceedings of 2016 American Control Conference*, Boston, MA, pp. 6803-6808.

The contributions of the co-authors are as follows:

- Associate Prof. Tegoeh Tjahjowidodo and Dr. Alf Kare Ådnanes suggested the initial project direction.
- I prepared the manuscript drafts. The manuscript was revised by Associate Prof. Tegoeh Tjahjowidodo, Associate Prof. Gerald Seet and Dr. Ricky Chan.
- I formulated the proposed strategy, performed the simulation studies and analyzed the results.
- I presented the paper in the American Control Conference 2016 in Boston, MA.
- Dr. Ricky Chan provided the data for the harbor tugboat operation profile in the case study.

Chapter 4 is published as Chan, R., Chua, L.W.Y., and Tjahjowidodo, T. (2016). “Enabling Technologies for Sustainable All-Electric Hybrid Vessels” (invited paper), *Proceedings of IEEE International Conference on Sustainable Energy Technologies (ICSET)*, Hanoi, Vietnam, pp. 401-406.

The contributions of the co-authors are as follows:

- Dr. Ricky Chan suggested the materials area and edited the manuscript drafts.
- Dr. Ricky Chan and I prepared the manuscript drafts. The manuscript was revised by Associate Prof. Tegoeh Tjahjowidodo.
- I formulated the proposed strategy, performed the simulation studies and analyzed the results.
- I presented the paper in the IEEE International Conference on Sustainable Energy Technologies 2016 in Hanoi, Vietnam.

Chapter 4 is published as Chua, L.W.Y., Tjahjowidodo, T., Seet, G.G.L., and Chan, R. (2018). “Implementation of Optimization-Based Power Management for All-Electric Hybrid Vessels” *IEEE Access*, 6, 74339-74354, DOI: 10.1109/ACCESS.2018.2883324.

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- Associate Prof. Tegoeh Tjahjowidodo is the corresponding author for the manuscript submission.
- I designed, source for components, liaise with vendors, built the signal interface and designed dSPACE control for the laboratory-scale hybrid power system test bed located in Mechatronics laboratory at the School of Mechanical and Aerospace Engineering.
- I built the MATLAB control models that can interface with the existing ABB control interface at the laboratory facility in MARINTEK, Trondheim.
- I conducted all the experimental validations, data collection and analysis of the results on the on the laboratory-scale hybrid power system test bed and at the laboratory facility in MARINTEK, Trondheim.
- Dr. Ricky Chan provided technical advices on the laboratory-scale hybrid power system test bed system design, component sizing and specifications. Dr. Ricky Chan also provided guidance on the scope of the experimental study at the laboratory facility in MARINTEK, Trondheim.
- Associate Prof. Tegoeh Tjahjowidodo provided guidance in the component sizing, dSPACE control software and assisted in the financial and procurement procedures of the laboratory-scale hybrid power system test bed components. Associate Prof. Tegoeh Tjahjowidodo also provided guidance on the scope of the experimental study at the laboratory facility in MARINTEK, Trondheim.
- Associate Prof. Gerald Seet provided guidance in the component sizing of the laboratory-scale hybrid power system test bed. Associate Prof. Gerald Seet also provided guidance on the scope of the experimental study at the laboratory facility in MARINTEK, Trondheim.

APPENDIX A is published as Chua, L.W.Y., Tjahjowidodo, T., Seet, G.G.L. and Chan, R. (2017). “Optimizing Fuel Savings and Power System Reliability for All-Electric Hybrid Vessels using Model Predictive Control”, *Proceedings of 2017 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, Munich, Germany, pp. 1532-1537.

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- I presented the paper in the IEEE/ASME International Conference on Advanced Intelligent Mechatronics 2017 in Munich, Germany.
- Associate Prof. Tegoeh Tjahjowidodo is the corresponding author for the paper submission.

27 March 2019

Date

Chua Wan Yuan, Liza

Acknowledgements

First and foremost, I would like to express my deepest gratitude to my supervisor, Associate Professor Tegoeh Tjahjowidodo, for his constant support in various aspects throughout my doctoral study. I am grateful for his patient guidance and insightful advice, which has helped me to overcome the challenges that I have faced in my research.

I would like to extend my heartfelt gratitude to my co-supervisor Dr Ricky Chan, for his constant encouragements, trust and support. His technical knowledge and insightful suggestions have helped me tremendously in the research. I would also like to express my sincere gratitude to my co-supervisor Associate Professor Gerald Seet for his guidance and constructive suggestions, which have helped me to focus my research in the right direction.

I would especially like to thank my former supervisor, Dr Jaspreet Singh Dhupia and former co-supervisor, Dr Alf Kåre Ådnanes for their advice and opportunities that they have given me throughout the time when I am under their guidance.

My appreciation extends to Ms Lee, Mr Seow and Mr Ng of Mechatronics Laboratory for their tremendous help over the past years, especially during the setting up of my test bed.

I would like to acknowledge Nanyang Technological University for the opportunity to pursue the doctorate degree and Singapore Economic Development Board for the Industrial Postgraduate Programme sponsorship. I would also like to thank ABB Pte. Ltd. for their financial support and collaborations in this programme.

To my parents and family, thank you for your unconditional love and care for me, and showing your support for me in various ways.

Last but not least, to my husband, Dennis, who has been with me in this whole journey through good and rough times. Thank you for being my greatest pillar of support and I would not have made it this far without you.

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Abstract

With the increasing concern in environmental impacts contributed by shipping industries, the International Maritime Organization set stringent requirements to monitor ship energy efficiency and ship emissions during operation. Some ships with highly dynamic loads, often face difficulty to maintain energy efficient operations with conventional mechanical propulsion design. Through technology advancements over the years, the all-electric hybrid power and propulsion system with DC distribution is the current state-of-the-art design, which can improve fuel efficiency and simplify the integration of DC power sources. However, the increased flexibility of the system and additional control requirements pose new challenges for power management control. The conventional rule-based (RB) power management strategies currently employed in the industry could not guarantee optimal control. An intelligent power management approach is necessary to address these challenges.

Hence, the main objective in this thesis is to propose a power management strategy for the optimal power allocation problem of an all-electric hybrid power and propulsion system with DC distribution, to improve fuel efficiency and to reduce emission. Firstly, dynamic models of the all-electric hybrid power system are developed in MATLAB\Simulink to simulate power system response. A laboratory-scale hybrid power system test bed is built in NTU to validate and calibrate the hybrid power system models. An instantaneous optimization-based power management strategy is then proposed, using the Equivalent Consumption Minimization Strategy (ECMS) concept, to determine the power allocation among the power sources that will result in minimal fuel consumption. A multi-level power management framework is then proposed for real-time execution of the strategy. Preliminary experimental testing and investigations on the laboratory-scale test bed shows satisfactory real-time performances. Subsequently, feasibility and performance of the proposed framework is validated on a full-scale system designed based on an actual all-electric hybrid vessel with DC distribution, in a laboratory facility in MARINTEK, Trondheim. Experimental results show the advantages of the proposed strategy with improvements in fuel saving over an improved RB strategy of up to 24.4%.

The proposed strategy is then enhanced in two areas. Firstly, the control objective is extended to include emission reduction. Among the major composition of ship

emissions (CO₂, NO_x, SO₂, HC, CO, PM), a tradeoff between NO_x emission and fuel consumption has been observed. Hence, a method is proposed to manage the compromise between fuel consumption and NO_x emissions, which allows the control on the influence of NO_x emission on the power split solution. Secondly, the flexibility of the proposed strategy to adapt to offshore applications is investigated. The control objective is refined for jack-up applications to include charge-sustaining due to the limited access to shore charging. A case study on tripping operations shows the effectiveness of the approach to maintain SOC within the target range, demonstrating the flexibility of the proposed strategy for more applications in the future.

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Nomenclature

Symbols

α	Penalty weighting on the SOC
c	Conversion factor
C_{batt}	Battery equivalent fuel consumption
C_{batt_min}	Battery maximum charging rate
C_{batt_max}	Battery maximum discharging rate
C_{eng}	Actual engine fuel consumption
$C_{total,eqv}$	Total instantaneous equivalent fuel cost
E_{charge}	Battery charging voltage
$E_{discharge}$	Battery discharging voltage
f_n	Governor full load speed
f_G	Grid frequency
f_0	Governor no load speed
$fuel(k)$	Instantaneous fuel consumption
H	Inertia constant
I	Current
J_{eq}	Equivalent inertia of the engine shaft
K	Battery polarizing constant
K_y	Engine torque constant
K_{NOX}	Control weighting for NO _x emission
$\dot{m}_{feq}$	Rate of total equivalent fuel consumption

$\dot{m}_{feq(normalized)}$	Rate of normalized sum of total equivalent fuel consumption
$\dot{m}_{fmax}$	Rate of maximum total equivalent fuel consumption
$\dot{m}_{NOxeq}$	Rate of total equivalent NO _x emission
$\dot{m}_{NOxmax}$	Rate of maximum total equivalent fuel consumption
mCO_2	Mass of CO ₂ emitted
η_{batt}	Efficiency of battery
n_m	Engine rotational speed
N	Number of engine cylinders
Nc	Control horizon
n_{batt}	Efficiency of battery
n_{dcdc}	Efficiency of Bidirectional DC-DC converter
n_{dt}	Efficiency of drive-train
η_e	Efficiency of electric motor
n_{eng}	Efficiency of engine
Np	Prediction horizon
P-f	Power-frequency
P_{batt}	Battery power
$P_{batt_min},$ $P_{charge,max}$	Maximum power during battery charging
$P_{batt_max},$ $P_{discharge,max}$	Maximum power during battery discharge
$P_{batt,ref}^*$	Battery power reference
P_e	Electric motor power

P_{eng}	Engine power
$P_{eng,min}$	Minimum engine power
$P_{eng,max}$	Maximum engine power
$P_{eng,rated}$	Maximum continuous rating of the engine
P_{gen}	Generator power
$P_{G,ref}^*$	Genset power reference
$P_{G,on}$	Power level for genset to be switched on
$P_{G,opt}$	Genset optimal loading point
P_{load}	Total load demand
Q	Battery maximum capacity
Q_n	Battery nominal capacity
$Q-V$	Reactive power-voltage
s	Equivalence factor
SFC	Average fuel consumption of battery
$SNOX$	Specific NO _x emission
$SOC(N)$	SOC of battery at N step
SOC_f	Desired final value of SOC of battery
SOC_{min}	Minimum SOC limit of battery
SOC_{max}	Maximum SOC limit of battery
T_e	Electric motor torque
T_{em}	Electromechanical torque of the synchronous generator
T_m	Engine output torque
V_{batt}	Battery voltage

V_{DC}	DC grid voltage
VAC	Voltage (AC)
VDC	Voltage (DC)
w	Desired reference input
ω_m	Engine angular speed
x_d	Direct-axis synchronous reactance
x_d'	Direct-axis transient reactance
x_d''	Direct-axis sub transient reactance
x_q	Quadrature-axis synchronous reactance
x_q''	Quadrature-axis sub transient reactance
τ	Engine time delay
τ_c	Engine time constant
T_d'	Transient time constant
T_d''	Sub transient time constant
Y	Engine fuel index
Δt	Time step

Abbreviations

AC	Alternating Current
A/D	Analog-to-Digital
AES	All-Electric Ship
AHTS	Anchor Handling Tug Supply Vessel
AVR	Automatic Voltage Regulator

CO ₂	Carbon Dioxide
D/A	Digital-to-Analog
DC	Direct Current
DP	Dynamic Programming
ECA	Emission Control Areas
ECMS	Equivalent Consumption Minimization Strategy
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operation Index
ESS	Energy Storage System
GA	Genetic Algorithm
GHG	Greenhouse Gases
HC	Hydrocarbons
HEV	Hybrid Electric Vehicles
H ₂ O	Water Vapor
HVAC	Heating, Ventilation And Air Condition
IMO	International Maritime Organization
IPA-SQP	Integrated Perturbation Analysis And Sequential Quadratic Programming
Li-ion	Lithium Ion
LTV-MPC	Linear Time Varying Model Predictive Control
MIP	Mixed-Integer Programming
MPC	Model Predictive Control
N ₂	Nitrogen
NMPC	Nonlinear Model Predictive Control

NO _x	Nitrogen Oxide
OSVs	Offshore Supply Vessels
PHEV	Plug-In Hybrid Electric Vehicles
PI	Proportional-Integral
PM	Particulate Matter
PMSM	Permanent Magnet Synchronous Motors
PPR	Pulse Per Revolution
QP	Quadratic Programming
RB	Rule-Based
RTI	Real-time Interface
SEEMP	Ship Energy Efficiency Management Plan
SFM	Sensitivity Function Method
SFOC	Specific Fuel Oil Consumption
SMPC	Stochastic Model Predictive Control
SO _x	Sulphur Oxides
SOC	State-of-Charge
THD	Total Harmonic Distortion

Chapter 1

Introduction

In the Introduction, the background and motivation towards all-electric hybrid power and propulsion system in the maritime industry are explained. The all-electric hybrid power and propulsion system brings about challenges in the power management control, which drives the main objectives of this work to develop advanced power management strategies to address these challenges.

1.1 Background and motivation

The shipping sector contributes significantly to the global economy as it is responsible for about 90% of global freight transportation. Diesel engines are the prime movers for most marine vessels, to provide the propulsion power for vessel maneuvering and electricity generations onboard. During fuel combustion process, diesel engine emits Nitrogen (N_2), Oxygen (O_2), Carbon Dioxide (CO_2), water vapor (H_2O), as well as small quantities of Sulphur Oxides (SO_x), Nitrogen Oxide (NO_x), Carbon Monoxide (CO), partially reacted and non-combusted hydrocarbons (HC) and particulate matter (PM) [1].

Among these shipping emissions, CO_2 has become an increasing global climate concern as it dominates the global warming potential among the greenhouse gases (GHG) emissions. Currently, the marine industry contributes to about 3% of the global CO_2 emission, but it has become a cause of concern as CO_2 emissions from shipping are projected to grow by up to a further 250% by 2050 due to potential increase in international traffic from projected economic growth, if no actions are taken [2]. In addition to the concern over GHGs, air pollutants such as SO_x and NO_x

cause treats to the environment, human health and eco-system [3]. SO_x and NO_x from shipping contributes to approximately 12% and 13% of the total global SO_x and NO_x respectively [4]. Shipping contributes a significance amount of SO_x as the fuel used in international shipping contains on average 2700 times more Sulphur than the fuel used for land-based vehicles [5]. It has been reported that NO_x emissions from international shipping around Europe may even surpass total land-based emission sources (including domestic shipping) in the 27 European Union member states combined by 2020 [5].

To tackle the climate impacts of shipping, the International Maritime Organization (IMO) introduced various regulation measures under a revised MARPOL Annex VI – Prevention of air pollution from ships in 2011, to control emissions level. Under the amendments, Energy Efficiency Design Index (EEDI), Energy Efficiency Operation Index (EEOI) and Ship Energy Efficiency Management Plan (SEEMP) are introduced to target at improving ship energy efficiency to reduce CO_2 emissions. Emission Control Areas (ECAs) are introduced, that sets tighter emission limits on SO_x , NO_x and PM for vessels operating in these areas [2, 6].

Conventionally, ships use diesel-mechanical propulsion system as the design is less complex and cheaper to construct. In such system design, the main engines are used solely as the prime mover for propulsion, with direct mechanical connection to the propellers. Other services and hotel load such lighting, Heating, Ventilation and Air Condition (HVAC) are supplied by auxiliary engines. Therefore, the main diesel engines are designed to meet the maximum required propulsion power, and the engines have to operate even when a small amount of thrust is required. This design might be suitable for ships cruising for long duration such as bulk carriers and tankers, since the propulsion load demand remains fairly constant. The engines can be sized according to the propeller's thrust required during cruising to operate within the optimal operating range. However, vessels such as tugboats, Offshore Supply

Vessels (OSVs) have large variation in their load demand for different modes of operations, which makes it difficult to maintain the engine operation within the designed optimal range. The problem can be illustrated through an example of the *tugboat dilemma*. Tugboats operation profile tends to be dynamic in terms of power requirements and duration. The power requirements are vastly different between the three main modes of operation broadly categorized as (i) transit, (ii) standby or idle, and (iii) ship assist operation. The tug load distribution, consolidated from operational data provided by ship operators [7] is illustrated in Fig 1.1 as represented by solid line. With the conventional mechanical propulsion design, engine are sized to the bollard pull requirements, while spending only a fraction of operation time at this power level. Tugs tend to spend the majority of their time in the transit and standby mode, but the power requirement is typically low in these two operational modes. With reference to the engine Specific Fuel Oil Consumption (SFOC) curve represented by dotted line in the same figure, operating under low engine loading leads to higher fuel consumption and GHG emissions.

As an alternative, electric propulsion can offer a solution for more energy efficient operation for such vessels [8]. Over the years, with technology advancements in motor drives controls and power electronics, new application areas have emerged to include sustainable power sources and energy storage such as batteries, super capacitors, ultra-capacitors and fuel cells to electric propulsion design for maritime applications [9, 10]. With the flexibility to optimize the load allocation among multiple power sources, these all-electric hybrid power and propulsion system architecture are capable of reducing fuel consumption and emissions by 10% to 35% according to [11].

The all-electric hybrid power and propulsion system with DC distribution is the current state-of-the-art in the industry. The modern DC distribution system offers multiple advantages over conventional AC power distribution system [7, 12-14]. The

main advantages include improving fuel efficiency, as well as the easy integration of DC hybrid power sources. One example is the ABB's Onboard DC Grid™ design [12] as shown in Fig. 1.2, which has demonstrated fuel savings and improved efficiency on OSVs and harbor tugs operations [15-17]. Along with the global environmental conservation trends, there is a growing interest in the maritime industry towards adopting the all-electric hybrid power and propulsion system to reduce fuel consumption and greenhouse gases emissions.

Figure 1.1 Tug load distribution vs SFOC curve

Figure 1.2 ABB's Onboard DC Grid™

1.2 Problem statement

The all-electric hybrid power and propulsion system with DC distribution increases the flexibility to split the load among multiple power sources. However, this also increases the challenges of conventional rule-based/heuristic power management control.

Firstly, as the number of power sources in the hybrid power system increases, the degree of freedom in power allocation control increases. At present, majority of the ship power management control in the industry relied on conventional rule-based (RB)/heuristic techniques. Examples of RB technique implementation are presented in [15, 18], where the battery usage is determined based on load dependent rules. In low loading conditions, batteries are used to supply required load power. In high loading regions, the engines are switched on and the battery will assist to provide additional power when necessary. Generally, rule-based techniques require the knowledge and the past experience of the system integrators and operators. For conventional and simple systems such as diesel mechanical propulsion system, load dependent rules could be sufficient. However, for advanced marine power and propulsion system with energy storage and renewable sources, the control concept is relatively new and managing the power split between different power sources of the hybrid power system is a complex task. Due to the increase in the degree of freedom in power allocation, designing the control rules for every combination of power allocation and loading condition becomes complicated, and optimal operation is not guaranteed.

Secondly, each vessel types places priority on different control objectives. Naval vessels tend to have short pulsed loads related to weapons utilization and control focuses at maintaining system reliability to handle such pulsed loads. Passenger ferries are usually subjected to low emission and low noise operation requirements. Tugboats have multiple modes of operation, requiring full designed bollard pull

power during ship assist, and relatively low power during transit and standby, and may face stricter requirements on vessel emission when operating near urban areas. The diverse operating profiles and control objectives makes it difficult to optimize the hybrid power system performance over a single operating point during the design stage or apply common rules across all vessel types.

Besides, a reduction in fuel consumption will reduce emissions if they are directly proportional to fuel consumption. Majority of the research work concentrates on achieving a reduction in fuel consumption. However, among the major composition of ship emissions, a tradeoff between NO_x emission and fuel consumption has been observed [1, 19]. Operating the engine in the most fuel-efficient range will result in an increase production of NO_x emission. Therefore, power management control faces additional challenge to maintain fuel efficient operations while ensuring that the NO_x emission regulation limits are met.

Similarly, for offshore applications such as jack-up rigs, during critical operations such as drilling, maximum power from all engines will be given, as the condition of the seabed during drilling might not be fully predictable. This is to prevent blackout, causing failure during the critical operation when there is a sudden load increase due to obstructions. Therefore, the efficient use of fuel is often at a much lower priority. However, with the increasing level of environmental concerns, the need for advanced power system and more fuel-efficient operation may be necessary in the near future.

To address these challenges and achieve substantial reduction in the fuel consumption and emission to justify the increase in cost and complexity of a hybrid power system, intelligent power management approaches are necessary [20].

1.3 Objectives, scope of work and approach

1.3.1 Objectives

The main objectives of this work are, firstly to propose a power management strategy and implementation framework for a given all-electric hybrid marine power system that can optimize fuel efficiency and reduce emissions. Secondly, to address the compromise between fuel consumption and NO_x emissions. Lastly, to investigate and demonstrate the flexibility of the proposed power management framework for different marine and offshore applications.

1.3.2 Scope of work

Optimization-based methods have been widely researched in the power management control for automobile hybrid electric vehicles (HEVs) and have shown great potential in application on all-electric ship (AES), mainly in the area of naval applications. While optimization-based approaches for power management of HEVs are matured, the power management in vessel applications faces a different set of challenge that needs to be addressed. Hence, in this work, the focus is to develop optimization-based methods for the power management problem of the commercial-based all-electric hybrid power system with DC power distribution. The scope of this research work includes:

1. *A mathematical model of an all-electric hybrid power system for power management studies.* The individual components of an all-electric hybrid power system can be modelled based on existing literature, to capture the relevant component dynamics while designing the proposed power management strategy. To understand the power system dynamics and to validate and calibrate the models on an actual system, a laboratory-scale hybrid power system test bed will be set up.

2. *Formulation of the optimization-based power management strategy.* The main power management problem considered in this work is the optimal power split between the power sources, to optimize fuel consumption and to manage the compromise between fuel consumption and NOx emissions. The proposed power management strategy will be designed as a supervisory level control, in order to integrate with existing power management control of the system. Hence, the fuel consumption and emission at steady-state values are considered, while fuel consumption and emission during engine ramping is not within the scope of this study.
3. *Experimental validation of the proposed power management approach for real-time application on actual system.* Experimental validation for power management studies on marine power system are not easily achieved due to the cost and space requirements of a test set up, but necessary to validate the proposed strategy for real-time practical implementations. Therefore, it is part of the scope of this work to validate the proposed strategy on a full-scale system.
4. *Demonstrates the proposed power management approach for offshore applications.* The proposed approach will be used to formulate the power management strategy to meet the control requirements for offshore applications, in particular, for jack-up rig operations.

1.3.3 Approach

The development of the optimization-based power management control strategy takes a progressive approach. First, the control objective considers fuel consumption minimization. Simulation models of the hybrid power system are developed on the MATLAB\Simulink platform to simulate the system response of the proposed control strategy.

Next, the proposed control strategy and implementation framework will be validated on physical system. Due to the space constraints to build a full-scale test set up, a laboratory-scale hybrid power system test bed is built in NTU Mechatronics lab for preliminary experimental investigations and development of the power management framework for real-time implementation, to prepare for the final validation on a full-scale system. The dynamic response of the simulation models of the hybrid power system will be calibrated and validated on this test bed set up. Final validation will be conducted on a full-scale system designed based on an all-electric hybrid vessel with DC distribution, in a laboratory facility in MARINTEK, Trondheim.

Finally, building on the proposed strategy, the control objectives will be extended to consider NO_x emissions, as well as extending to offshore applications.

1.4 Organization of the thesis

The structure of the thesis is illustrated in Fig. 1.3. Chapters 2 to 4 mainly focus on the development of the proposed optimization-based power management strategy based on Equivalent Consumption Minimization Strategy (ECMS) approach, and the validation of the proposed strategy on an actual system. Chapters 5 and 6 describe the enhancements of the proposed strategy, considering additional control objectives on different marine and offshore applications. Chapter 7 highlights the contributions and discusses about the future works.

Figure 1.3 Structure of the thesis

A brief overview of the chapters is given as follows:

Chapter 2 covers an overview of the different ship power and propulsion systems, and the existing ship power management control strategies employed in the industry for each system are first introduced. An extensive review of the literatures on the developments of optimization-based strategies in automotive hybrid electric vehicles is conducted and three main optimization-based approaches are discussed in detail. Finally, optimization-based strategies for electric ships are discussed for specific ship types.

Chapter 3 includes the system description of the laboratory-scale hybrid power system test bed built in NTU Mechatronics lab. The key components of the hybrid

power system are modelled in MATLAB\Simulink. The transient and steady-state response of the simulation models are validated and calibrated against the laboratory-scale test bed, and validation results are presented and discussed.

Chapter 4 first introduces the concept of ECMS. The power management problem is formulated according to ECMS approach to minimize fuel consumption. A multi-level power management framework is then proposed, to apply the optimization solution to existing power management system. Preliminary studies on the proposed strategy is done through simulation and the real-time implementation is investigated on the laboratory-scale hybrid power system test bed. An improved rule-based strategy is introduced to set as a benchmark to evaluate the performance of the proposed ECMS. Finally, the proposed framework is validated on a full-scale system in a laboratory facility located in MARINTEK, Trondheim. The experimental procedures are illustrated in detail. Finally, the experimental results are presented and discussed.

Chapter 5 presents the enhancement of the proposed ECMS to multi-objective power management to consider both fuel consumption and emissions. The engine emission trends are first analyzed. Following which, a novel method to design the equivalent cost with the use of weighting factor is proposed, to manage the compromise between fuel efficiency and NO_x emission reduction. The feasibility of the proposed approach is demonstrated through case studies over harbor tugboat operations. Simulation results are presented and discussed.

Chapter 6 presents the enhancement of the proposed ECMS for jack-up rigs operation. An overview of the modes of operations of jack-up rigs is first described. The proposed ECMS is modified to include charge sustaining control. The feasibility of the proposed strategy for this application is evaluated over a case study of the draw works pipe tripping operations. Simulation results are presented and discussed.

Chapter 7 concludes major findings and main contribution of this work and suggests recommendations for future work.

Chapter 2

Literature Review

In this chapter, an overview of the different ship power and propulsion system, and the existing ship power management control strategies employed in the industry for each system are first introduced. An extensive review of the literatures on the developments of optimization-based strategies in automotive hybrid electric vehicles is conducted and three main optimization-based approaches are discussed in detail. Finally, optimization-based strategies for electric ships are discussed for specific ship types.

2.1 Diesel-mechanical propulsion

A conventional diesel-mechanical propulsion system is shown in Fig. 2.1. The main engines are directly coupled to the propellers through a gearbox to drive the main propulsion system. The auxiliary engines are connected to an AC distribution network to distribute the generated electric power for hotel and other service loads of the vessel as such lighting and heating, ventilation and air condition (HVAC). The main advantage of this system is minimal transmission losses as there is a direct mechanical connection between the diesel engines and propellers. The disadvantages include poor fuel efficiency and high emissions when the engines are operating at low thrust, and the lack of redundancy as the failure of either main engines will lead to loss of propulsion.

Power management control is straightforward since both main engines have to operate, regardless to the amount of thrust required. Hotel and service loads are relatively constant for the auxiliary engines.

Figure 2.1 Conventional diesel-mechanical propulsion system

2.2 Diesel-electrical propulsion system

Diesel-electric propulsion is a proven solution in many marine applications, such as cruise vessels, ferries, Anchor Handling Tug Supply vessel (AHTS), Dynamic Positioning (DP) drilling vessels, pipe-laying vessels, war ships and more [8, 9, 21-24]. A simplified example of a diesel-electric propulsion system with AC distribution is shown in Fig. 2.2. In this example, the system consists of two main diesel engine generator sets (gensets), connected to the electrical switchboards, which allows the distribution of electrical power for the whole vessel. The AC power from the electrical switchboard is fed through the frequency converter drives, which consist of AC-DC rectifier and DC-AC inverter, to power the main propulsion units.

Transformers are usually required to reduce the total harmonic distortion (THD) in the system to meet the requirements of the marine classifications society.

With this system design, the number of operating gensets can be controlled based on the power demanded to improve the engine loading and fuel efficiency. The reduction in fuel consumption is more significant for vessels with large load variations. Fuel savings of 17% can be observed by using diesel-electric propulsion on AHTS as compared to using diesel-mechanical propulsion [8, 21]. Furthermore, diesel electric propulsion system allows greater flexibility in positioning of the thrusters and greater convenience in maintenance since electrical connection requires smaller footprint than mechanical links. Also, there is redundancy in the power system. In the unlikely case where one of the main engines experiences a failure, the other generators can provide necessary propulsion power. However, the main disadvantage as compared to the conventional mechanical propulsion design is the power transmission losses due to addition of electrical components such as the electrical motor and couplings between the main engines and the propellers. Also, it requires the synchronization of the engines at the AC distribution network frequency.

With the system loads and power sources connecting to the same electrical network, voltage and frequency swings due to fault conditions or power supply and demand mismatch can result in the shutting down of the electrical system. Hence, the control strategies for the electrical network is targeted at maintaining the voltage and frequency stability of distribution line, load sharing among the gensets, protection control and blackout preventions.

Figure 2.2 Diesel-electrical propulsion system

2.2.1 Frequency and voltage control

In an electrical propulsion AC distribution network, engines are operated at rated speed to maintain the frequency on the AC distribution network. The engine speed is controlled by the engine governor, which can operate in isochronous control or speed droop control. Isochronous control can be used when a single genset is connected to the network, with temporary change in speed as load changes. However, droop control is often necessary to maintain the stable operation of the AC distribution network, especially when two or more gensets are connected in parallel. In a system without droop, an increase in load will slow down the engine. The governor will respond by increasing the fuel to bring the engine speed back to the original speed. However, due to the inertia and power lag, the engine speed increases beyond its original speed, causing an overshoot. The governor will respond in the opposite direction to reduce the fuel to reduce the engine speed and this results in an

undershoot condition. The over-correction in both directions results in instability, which will amplify and eventually trip the engine.

With droop control, the governor speed setting is reduced as the load increases. This lower speed setting mitigates the problem of speed overshoot when governor responds under an increase in load. The amount of droop can be calculated based on:

$$\% \text{droop} = \frac{\text{No load speed} - \text{Full load rated speed}}{\text{Full load rated speed}} \times 100 \quad (2.1)$$

The common recommended droop setting is 3% to 5% [25]. The amount of droop and the governor speed setting determines the amount of load the engine will carry, as illustrated in power-frequency (P - f) characteristics shown in Fig. 2.3 (a). At governor no load speed setting f_0 , engine is loaded at 50% at when the grid frequency is at f_G . As the engine load increases, governor speed setting reduces along the droop line. At full load, governor speed setting will be at f_n . If the same grid frequency is desired at full engine load, the governor no load speed setting can be increased to f_0' and the engine will deliver full load power at f_G . Changes in both the no load speed setting, as well as the droop percentage, can affect the engine load.

Speed droop controls the load sharing of active power among the gensets running in parallel [11, 26]. In the case of two or more engines, the proportion of load sharing between the engines depends on the speed droop setting of each engine, as illustrated in Fig. 2.3 (b). If both engines have the same droop setting, they will each share load proportionally as indicated by the solid line. An increase in the governor no load speed setting of engine 2 will shift the droop line upwards, and a decrease in the governor no load speed setting of engine 1 shifts the droop line downwards. Under this new setting, genset 2 will carry the full load demand, engine 1 load reduces to zero.

Figure 2.3 (a) Governor speed droop control (b) P - f droop characteristics and active load sharing

The output voltage of the genset is maintained by Automatic Voltage Regulator (AVR) of the generator. Similarly, voltage droop control is implemented to control the load sharing of the reactive power between the parallel running gensets [26]. The amount of droop can be calculated based on:

$$\% \text{droop} = \frac{\text{No load voltage} - \text{Full load rated voltage}}{\text{Full load rated voltage}} \times 100 \quad (2.2)$$

The concept of reactive power-voltage (Q - V) droop control is similar to P - f droop control as illustrated in Fig. 2.4 (a) and (b).

Figure 2.4 (a) AVR voltage droop control (b) Q - V droop characteristics and reactive load sharing

2.2.2 Power management system

The frequency and voltage setpoints, as well as the number of running gensets, protection control and blackout prevention are usually managed by the power management system. The number of running gensets can be optimized based on the load conditions, to allow the engines to operating within the fuel-efficient region. Based on the engine fuel consumption data, studies have shown that in certain load conditions, equal load sharing among equal sized gensets is more optimal, while for lower load conditions, it might be more fuel efficient to run lesser units with higher load [27, 28]. With these conditions, a conventional rule-based strategy is typically used, where rules are formulated to determine the control actions of switching the gensets on and off based on the load demands [29, 30].

2.3 All-electric hybrid power and propulsion system with modern DC power distribution

In recent years, the all-electric hybrid power and propulsion system with DC distribution has been the state-of-the-art solution, as briefly described in the earlier chapters. An all-electric hybrid power and propulsion system with DC distribution is depicted in Fig. 2.5. In this system, the main power sources comprise of gensets and energy storages such as batteries, super/ultra-capacitors, or combinations of multiple sources. An AC-DC rectifier is used to convert AC power from the gensets to DC. Power from both genset units and energy storage are distributed through DC distribution system to supply propulsion, service and hotel loads.

Figure 2.5 All-electric hybrid power and propulsion system with DC distribution

A significant advantage of using a DC distribution system as compared to a conventional AC distribution is that the generator frequencies do not need to be synchronized. Hence, variable speed engines can be used, which can achieve a more fuel-efficient operation as compared to fixed speed engines used in conventional AC distribution. Operating engine at rated speed during low loading condition consumes more fuel. By adjusting the engine operating speed between 60%-100% of the rated engine speed, the variable engines can achieve a lower SFOC as compared to fixed speed engine, especially in low loading conditions. SFOC indicates the amount of fuel consumed to produce a unit kilo-watt hour of energy. The general trend of SFOC obtained from engine manufacturer's data is as shown in Fig. 2.6.

Another advantage of the DC distribution is that it prepares the system for integration of energy storage devices, as well as renewable energy sources in future developments. These sources are mostly DC and integration to a DC power

distribution network will be more straight forward. The integration of energy storage device has large potential in fuel savings and emission reduction. For example, batteries can be used to provide power during low loading conditions without the need to operate the engines, achieving zero emission operation. In addition, shore power can be utilized. Batteries can be charged using shore power when ship return to harbor, and discharge to supply power during ship operations off the shore. This maximizes the advantages of shore power which is cheaper and produces less hazardous emissions.

Furthermore, hybrid all-electric propulsion encompasses not only the advantages of reduction of fuel consumption and emission, but also reduction of engine running hours with batteries, which can reduce life cycle and maintenance costs. Also, main switchboards and propulsion transformers can be omitted with the DC power distribution system design, contributing to pay-load space savings and more flexibility in arranging the power system components.

Figure 2.6 SFOC of a fixed speed engine and a variable speed engine

2.3.1 Voltage droop control

In a DC power distribution system, the balance of power generation and consumption is achieved through voltage droop control. When two or more generators are in parallel, the load sharing among the generators depends on the droop characteristic of the generator as shown in Fig. 2.7.

Figure 2.7 Voltage droop characteristics of (a) Two gensets (b) Two gensets with battery

As illustrated in Fig. 2.7 (a), at DC grid voltage V_0 , the generators share the load at P_{G1} and P_{G2} according to their respective droop. Equal load sharing can be achieved if the generators have equal droop. The droop percentage and voltage set points $V_{set,1}$ and $V_{set,2}$ of genset 1 and 2, respectively, can be adjusted to achieve the desired load sharing between the parallel running gensets. In [31], droop control is implemented to control the load sharing between the gensets and battery, as illustrated in Fig. 2.7 (b). At the initial voltage V_0 , battery supplies zero power while genset 1 and 2 shares the load at P_{G1} and P_{G2} , respectively. A sudden reduction in load will result in the increase in voltage. As power electronics response much faster than the gensets, the excessive power in the system is first absorbed by the battery, indicated by P_{batt}' . As the battery voltage setpoint increases from V_0 to V_1 , battery power gradually reduces to zero and the load will be shared by genset 1 and 2 at P_{G1}' and P_{G2}' respectively.

The utilization of battery in this case mainly helps to improve the robustness of the power system during load fluctuations and prevents under voltage conditions during large load changes.

2.3.2 Energy storage system control

Energy storage devices serve for wide range of control objectives such as system redundancy, system response, fuel efficiency, emission reduction and more. In [32, 33], a list of functions of the energy storage device that has been implemented in an actual ship system are described as follows:

- **Spinning reserve**
Ensures that battery has sufficient energy as a backup to step in immediately to take on the load for a pre-defined period of time, during sudden loss of generating capacity. This can help to reduce the number of gensets online as backup, hence reducing fuel consumption and emission, as well as engine running hours.
- **Enhanced ride through**
Similar to the function of spinning reserve, but it is implemented on a local sub-system level, functioning as uninterrupted power supply (UPS). This ensures the power system availability.
- **Peak shaving**
The battery will be responsible for the peak loads and load variations in the system, such that the gensets can supply the average load power. This function can avoid the need to start a new genset to supply for short peaks, hence improving the fuel efficiency of the system and reduce engine running hours.

- Enhanced dynamic support

The battery absorbs high ramping load changes such that the genset sees a gradual increase or decrease in load, employed together with peak shaving function. Similarly, this can improve the system response on fast load changes.

- Strategic loading

The battery charging and discharging power is controlled to maintain the engine within the fuel-efficient operating range, hence optimizing the fuel efficiency of the gensets.

- Zero emission operation

The engines are switched off and battery becomes the main source of power. Without operating the engine, there will be no emissions and fuel consumption.

These functions can be implemented independently, as well as in parallel, depending on the ship operation requirements.

2.3.3 Rule-based/Heuristics power management strategies

The all-electric hybrid power and propulsion system presents a potential to optimize fuel efficiency and to reduce emissions due to its flexibility to control multiple power sources and the use of energy storage device. An upper layer of power management control strategy is required in the power management system to manage the power split between the multiple power sources and optimize the use of the energy storage functions, on top of the primary power management system functions that regulates the vessel performance such as voltage stability, protection control and blackout prevention. Rule-based (RB)/heuristics method is a basic approach to resolve this power management problem.

In [7, 15], an example of rule-based control for all-electric hybrid tugs is described, where the application of battery is determined based on the modes of operation of the harbor tug. As mentioned before, the tug operation can be classified under three modes of operations, i.e. (i) transit, (ii) standby or idle, and (iii) ship assist operation. The power flow from the power sources are depicted in Fig. 2.8 (a), (b) and (c) for each of the operation mode, respectively. During standby or idle condition, the power demand is usually low, and battery can be used to power the tug load requirements. In transit operation, load demand is increased and one genset is started. To allow the genset to operate within the fuel-efficient region, excessive power can be used to charge the battery. Only in ship assist operation, both genset are started, to ensure power availability during the operation. The battery can charge or discharge, depending on the engine load.

In [18], a loading ratio is pre-determined for the gensets, which sets the control rules for charging and discharging of the battery based on the genset load. When the gensets are operating at low loading condition, battery is set to charge in order to increase the genset loading to the efficient operating range. When genset are operating in unfavorable high loading, battery are set to discharge to reduce the loading on the genset.

Majority of the advanced power and propulsion architectures in the maritime industry are using these conventional rule-based/heuristics techniques, which depend largely on the past experience of the system integrators and operators. However, such technique could not ensure the optimality of the power split between the power sources. Literature has shown that optimization-based approaches demonstrate better performance in reduction of fuel consumption or emissions, as compared to rule-based/heuristics methods. This will be reviewed in the next section.

Figure 2.8 Power flow during (a) Standby/Idle (b) Transit (c) Ship assist

2.4 Optimization-based power management strategies

2.4.1 Overview of optimization-based approaches

In optimization-based approaches for power management control, the goal of the controller is to minimize the cost function. The power management problem is solved as an optimization problem, where the cost function is formulated based on the desired control objectives. Cost function can include fuel consumption, emission, or other cost factors depending on the application. When multiple cost factors are encompassed in the cost function, weighting functions can be allocated for each cost factors, to control the influence of the cost factors on the solution.

Optimization-based power management strategies for hybrid electric vehicles (HEVs) have been widely researched. In contrast, studies for such approaches for marine applications started only in the recent years when ship electrification and hybridization gains popularity. Knowledge can be built upon the studies in HEVs application to develop a suitable optimization-based power management control and implementation framework for all-electric hybrid power and propulsion system. Hence, studies are first conducted on optimization-based methods employed in HEVs to understand fundamental theories and identify possible methods that can be adopted for the all-electric hybrid marine power system.

In the power management of HEVs, optimization-based approaches are generally classified into two categories [34-36], i.e. instantaneous optimization and global optimization. Instantaneous optimization involves solving the instantaneous cost function at each optimization time step. The instantaneous cost function depends only on the present state of the system, and hence can be applied in real-time. However, since optimization considers only the current state, solution is locally optimal along the full operation cycle. Global optimization on the other hand, considers the full operation cycle to determine a global optimal solution. Hence, very often, global optimization methods are performed offline and used as a benchmark to evaluate the optimality of the instantaneous optimization solutions. From various literature studies on power management of HEVs, Equivalent Consumption Minimization Strategy (ECMS) and Dynamic Programming (DP) are the two most widely researched instantaneous and offline methods respectively. More recent work on optimization-based power management have also looked into predictive approaches such as the Model Predictive Control (MPC). The following review in the application in HEVs will focus on theoretical formulation and examples of these three methods. Fig. 2.9 illustrates an overview of off-line, instantaneous and predictive power management [37], based on the concept illustrated earlier.

Figure 2.9 Overview of optimization-based approaches (reproduced from [37])

2.4.2 Application in automotive hybrid electric vehicles

2.4.2.1 Dynamic Programming

Dynamic programming (DP) is a commonly employed method to solve for global optimal solution over the whole driving cycle in the power management control of HEVs [38-47]. DP solves for global optimum solution based on Bellman's principle of optimality.

The underlying concept of DP is optimization of a sequence of decisions to optimize each related subsequence. Therefore, DP results in an optimal trajectory of sequential decisions within predefined initial and final conditions, realizing a global optimization of the objective functions as depicted in Fig. 2.10.

The optimality resulting from DP depends on the number of grid points on the trajectory plan of the state of the system. Decrement of the size of stages as well as

steps increases the number of grid points and the optimality of the DP is increased consequently. However, the increase in the number of grid points leads to the increase of the computation load.

Figure 2.10 Dynamic programming (reproduced from [37])

In the case of HEV where the control objective is to minimize the fuel consumption, HEV model can be expressed in discrete state-space form:

$$x(k+1) = f(x(k), u(k)) \quad (2.3)$$

To minimize the fuel consumption, a general form of the cost function can be formulated as [45]:

$$\begin{aligned} J &= \sum_{k=0}^{N-1} [L(x(k), u(k))] + G(x(N)) \\ &= \sum_{k=0}^{N-1} [fuel(k)] + \alpha(SOC(N) - SOC_f)^2 \end{aligned} \quad (2.4)$$

Where L is the instantaneous at a particular stage, G is the cost at N step, $fuel(k)$ is the instantaneous fuel consumption, $SOC(N)$ is the SOC of battery at N step, SOC_f

is the desired final value of SOC, and α is the penalty weighting on the SOC. At each optimization time step, DP calculates every possible combination of engine and battery power to find the control input that gives the lowest cost.

Logically, to minimize the fuel consumption, the optimal solution will discharge the battery as much as possible. However, this solution is usually not desirable as batteries have a healthy discharge range, in order not to shorten the battery life cycle. Hence, the SOC variable is required in the cost function to keep the battery SOC within the depth-of-discharge range limits while generating a solution with minimal fuel consumption. Charge-sustaining control is necessary for HEVs, except for plug-in HEVs (PHEV) where battery can be recharged from external power source at charging station.

In [46], this cost function is further expanded to include emission control as follows:

$$J = \sum_{k=0}^{N-1} fuel(k) + \mu \cdot NO_x(k) + v \cdot PM(k) + \alpha(SOC(N) - SOC_f)^2 \quad (2.5)$$

where μ and v are the weightings of the NO_x and PM emissions respectively. NO_x and PM emissions are modelled in the cost function with emission maps, which can be obtained by scaling up the emission models of a smaller diesel engine in ADVISOR program.

In [41, 45, 47], DP shows a potential fuel savings of 5.56% to 30.75% as compared to conventional RB strategy. However, a well-known limitation of DP is the curse of dimensionality, where the number of states grows exponentially in n , for a system with n -dimensional state-space. This amplifies the computational burden, especially for large or complicated systems. Also, DP is an offline power management approach and the knowledge of full driving cycle is required before computation. Hence it is difficult to implement DP in real-time applications.

In most cases, DP is set as a benchmark for evaluation of the optimality of the other developed power management approaches. DP solutions are also used to formulate or to improve the optimality of power management controllers. Examples include the improved RB strategy [45, 46] and Stochastic Dynamic Programming (SDP) [48, 49]. RB strategy is improved by extracting the rules from the optimal results from DP solutions. In the SDP approach, Markov chain driver model is used to model the driving cycle power demand, based on the power demand statistic of multiple driving cycles. From the multiple driving cycles, transition probability of power demands from various sample driving cycles are estimated in real-time to obtain the sub-optimal solution.

2.4.2.2 Equivalent Consumption Minimization Strategy

Equivalent Consumption Minimization Strategy (ECMS) is a method first proposed in [50]. The main idea of ECMS is an equivalent fuel consumption for the battery energy used and based on charge-sustaining where the battery is never charged by external energy. The concept of the battery equivalent fuel consumption can be illustrated in Fig. 2.11. Based on the assumption that the amount of battery energy used will be recharged by the engines in the future, an equivalent fuel cost for battery energy can be derived by considering the average fuel required to charge the battery along the energy path from the engine to the battery. In the case of battery charging, it means that the engine can save on that same amount of energy in the future. Hence, the total equivalent fuel consumption will be subtracting the equivalent fuel consumption for the charged battery energy from the actual fuel consumption of the engine.

Figure 2.11 Equivalent consumption concept

The total equivalent fuel consumption to be considered in the cost function will be sum of the actual fuel consumption of the engine and the equivalent fuel consumption for the battery energy. In order to minimize the total equivalent fuel consumption, the cost function can be formulated as follows:

$$\min J = C_{eng} + C_{batt} \quad (2.6)$$

where C_{eng} is the actual engine fuel consumption and can be obtained from engine SFOC curve such as Fig. 2.6. C_{batt} is the battery equivalent fuel consumption that can be calculated as follows for the application of a series HEV:

$$C_{batt} = s \cdot \frac{SFC \cdot P_e}{3.6 \cdot 10^6} \begin{cases} \text{if } T_e < 0: s = \frac{1}{\eta_e \cdot \eta_{batt}}, SFC = SFC_{charge} \\ \text{if } T_e > 0: s = \eta_e \cdot \eta_{batt}, SFC = SFC_{discharge} \end{cases} \quad (2.7)$$

where s is the equivalence factor, P_e (W) is the electric motor power, SFC (g/kWh) is the average fuel consumption of the battery during charging and discharging. T_e (Nm) is the torque of the electric motor, where positive represents battery discharging, and negative represents battery charging. η_e and η_{batt} are the efficiencies of the electric motor and battery respectively. As SFC is usually

expressed in grams per kilo-watt hours, a scaling factor is required in the equation and C_{eng} and C_{batt} are expressed in grams.

Similarly, the ECMS approach can also be enhanced to include emission costs in [51-53]. To minimize both fuel consumption and NO_x emission, the cost function as proposed in [52] is as follows:

$$\min J = \dot{m}_{feq(normalized)} = (1 - \lambda_{NOx}) \cdot \frac{\dot{m}_{feq}}{\dot{m}_{fmax}} + \lambda_{NOx} \cdot \frac{\dot{m}_{NOxeq}}{\dot{m}_{NOxmax}} \quad (2.8)$$

where $\dot{m}_{feq(normalized)}$ (g/s) is the rate of normalized sum of total equivalent fuel consumption and emission, $\dot{m}_{feq}$ (g/s) is the rate of total equivalent fuel consumption, $\dot{m}_{fmax}$ (g/s) is the rate of maximum total equivalent fuel consumption, $\dot{m}_{NOxeq}$ (g/s) is the rate of total equivalent NO_x emission and $\dot{m}_{NOxmax}$ (g/s) is the rate of maximum total equivalent fuel consumption. Both the total equivalent consumption of fuel and NO_x emission are normalized to have an equal scale for comparison. λ_{NOx} is the control weighting to allow a control over the impact of NO_x emission reduction on the power management.

The equivalence factor is a crucial factor in affecting the results of the ECMS. Literature has shown different ways to calculate the equivalence factor, which can be broadly categorized into 4 groups [54]. First group derives a constant equivalent factor. In [50, 55], the constant equivalent factor is derived using the average efficiencies from the fuel to the battery and vice-versa. The second group pre-calculates the equivalent factors to achieve the least instantaneous fuel cost for all vehicle operating points [56]. The equivalent factors have to be re-calculated if the model parameters change. The third group calculates the equivalent factor in real time. The most common method uses a tangent function, to manage the battery SOC within designed range [57-59]. Other methods includes the rule-based ECMS method [60] and tuning using fuzzy logic [61]. The main disadvantage of the third

group is the tuning of the equivalent factor functions. A well-tuned function for a driving cycle might not work as well in another driving cycle. Lastly, the fourth group utilizes prediction methods such as the adaptive technique (A-ECMS) to calculate equivalent factor in real-time [62-66], which attempts to solve the problem in the tuning and computation of the changing equivalent factors, but has the risk of heavier computational burden.

ECMS demonstrates significant fuel savings compared to conventional RB strategies [47], and is able to achieve close to optimal solution when compared to DP approaches[59, 67, 68]. In addition to series and parallel HEVs, the application of ECMS has also extended to hybrid fuel cell vehicles [69-71] and more-electric aircraft [72].

2.4.2.3 Model Predictive Control

In more recent years, Model Predictive Control (MPC) has been investigated as an alternative approach for power management control of HEV. MPC predicts the required output to track the desired reference, based on the internal dynamic model of the plant that is defined in the controller. The mathematical plant model for the control design can be expressed as a state-space model as follows:

$$\begin{aligned}x(k+1) &= Ax(k) + Bu(k) \\ y(k) &= Cx(k) + Du(k)\end{aligned}\tag{2.9}$$

where A , B and C are the state matrices. $x(k)$ are the system states, $u(k)$ are the input variables and $y(k)$ are the output variables. Based on the internal model of the plant, the MPC is able to predict the future plant outputs and generate the required plant input within the prediction window by manipulating the state-space equation to (2.10).

$$\begin{bmatrix} y(k+1) \\ y(k+2) \\ \vdots \\ y(k+N) \end{bmatrix} = \begin{bmatrix} CA \\ CA^2 \\ \vdots \\ CA^N \end{bmatrix} x(k) + \begin{bmatrix} CB & 0 & 0 \\ \vdots & \ddots & \vdots \\ CA^{N-1}B & \dots & CB \end{bmatrix} \begin{bmatrix} u(k) \\ \vdots \\ u(k+N-1) \end{bmatrix} \quad (2.10)$$

where k represents the current time step, and N is the length of prediction window. A cost function subjected to constraints is formulated in Eq. (2.11) and solved using Quadratic programming to obtain the optimal control input which minimizes the cost function.

$$J = \sum_{i=1}^{Np} (y(k+i) - w(k+i))^2 + \lambda \sum_{i=1}^{Nc} (\Delta u(k+i-1))^2 \quad (2.11)$$

where $w(k+i)$ is the desired reference, Δu is the change in control input, Np and Nc are the prediction and control horizon respectively, λ is the weighting for the control inputs. Receding horizon control is implemented and only the first term of the control input is implemented to the plant. Measured output from the plant is fed back into the controller, which forms a closed loop control.

MPC demonstrates the ability for reference tracking and minimizing output error, as well as fuel savings in various power management studies. An example of the power management under MPC is shown in Fig. 2.12. The results is replicated from [73], where MPC is applied to a hybrid fuel cell vehicle for power-split control between the fuel cell (P_{fc}) and battery (P_b), and the proposed MPC achieves better fuel economy as compared to RB and ECMS. In [74], MPC is first proposed for power-split HEV, based on a linearized plant model, and demonstrated promising results in fuel economy over RB control in PSAT, a commercial HEV simulation software. In [75-77], a nonlinear MPC (NMPC) is proposed to further improve the fuel economy from linear time varying MPC (LTV-MPC), by including battery's SOC as an additional cost. Simulation is performed over PSAT, and the proposed NMPC shows

noticeable improvement in fuel economy over LTV-MPC, as well as RB control in the PSAT software.

Figure 2.12 Simulation results of MPC on hybrid fuel cell vehicle (Reproduced from [73])

In [78-80], stochastic MPC (SMPC) is proposed where Markov chain model is applied to represent future driver power request. The performance of the SMPC shows better fuel economy than cases assuming a constant power demand within the prediction horizon, but do not outperform cases where full driving cycle information is available. In [81], MPC is applied to a series hydraulic hybrid vehicle (SHHV), for regulating vehicle velocity, engine torque, speed, and accumulator pressure to

their corresponding reference values. Fuel economy is improved by tracking the optimal engine torque and speed references from the fuel map, which shows evident fuel savings as compared to Proportional-Integral-Derivative (PID)-based control.

Compared to ECMS, some cases shows that MPC is demonstrating better fuel economy [68]. However, two crucial factors that affects the performance of MPC is the accuracy of the prediction model, as well as the tuning of the penalty weightings. In some cases, large efforts are required to tune the penalty weights to achieve good results.

2.4.3 Application in electric ships

In comparison to power management of HEVs, power management of all-electric hybrid ship system faces its own set of challenges. Unlike HEVs, different ship types have their control priorities and requirements, and certain applications, such as naval vessels, deal with critical operations that are challenging to control. In addition, the load condition under different vessel mode of operations can vary in mega-watts range. Also, ship power system consists of more than one engine, and the number of engines to be operated in parallel is a part of the power management problem, whereas HEVs only deals with one engine.

In terms of control methodology, charge-sustaining control which is usually implemented in HEVs, is not compulsory since battery can be recharged from shore power, which is cheaper and emission free. Therefore, there is a greater flexibility to optimize the battery usage with the other power sources in the ship hybrid power system.

2.4.3.1 Naval applications

The power management control of naval vessels tends to focus on maintaining system reliability, redundancy, and handling of short pulsed loads related to weapons utilization. Fuel consumption and emission are of a lower priority in these cases. To achieve the mission effectiveness for all-electric naval vessels, in [82, 83], a sensitivity function method (SFM) is proposed to improve computational efficiencies of dynamic optimization. In [84, 85], the proposed SFM is fitted into a three level hierarchical controller for real-time implementation under normal mode of operation, as illustrated in Fig 2.13. The power split between the power sources for a specific mission is referred to as trajectory planning. The first two levels determine the long-term trajectory planning over a planning horizon N . First level uses Quadratic programming (QP) to determine battery and other power sources split, and second level uses SFM to plan the power split between gas turbine and fuel cell. The third level uses MPC for trajectory tracking to track the optimal power references from first two levels and rejects disturbances during real-time implementation. In [86], the proposed hierarchical control is adjusted to a two level reference governor based control for operation recovery and sustaining critical functions during operation failure.

In [87], nonlinear MPC (NMPC) is proposed for all-electric naval vessels to manage high-power electrical loads. High-power electrical loads are mainly modern advanced defense systems such as missile defense radar, electromagnetic rail guns, electromagnetic launch systems etc. The aim of the control is to reduce the high ramp rates of the primary generation sources and maintain stable operations under pulsed load condition. Both simulations and experimental validation on physical test bed have shown that the proposed NMPC is able to maintain system stability with voltage deviation less than 2.5% under repeated pulse load condition. This method is further improved in [88, 89], where the integrated perturbation analysis and

sequential QP (IPA-SQP) framework is proposed to reduce the solving time for NMPC, for the same system application. The feasibility of the proposed IPA-SQP based MPC is validated on a physical test bed. It is believed that the proven concept of real-time implementation of optimization-based method on a physical test bed laid a foundation for future development of optimization-based power management strategies for shipboard power systems. In [90], a combination of heuristics and MPC is proposed for the power management control under pulsed load. Heuristic control first evaluates if the pulse load power ramp rate is higher than the genset's ramp rate. If ramp rate of load exceeds genset limits, genset will provide the maximum ramp and energy storage will compensate for the difference. This can avoid switching on of additional genset to provide for the ramp, and hence, achieve better fuel efficiency. However, the maximum discharging rate of energy storage is not considered. In physical energy storage devices, there is a maximum charging and discharging rate, depending on the type of battery cell.

Figure 2.13 Multi-level hierarchical control for all-electric ship

2.4.3.2 Commercial vessels

MPC is frequently proposed for commercial vessels to minimize power tracking error and manage power fluctuations to maintain system stability. In [91-93], MPC is developed to optimize the power split between the hybrid energy storage system (HESS) consisting of batteries and ultra-capacitors (UC) to deal with power fluctuations for a general all-electric power and propulsion system. Power tracking error is used as a measurement for the effectiveness in mitigating power fluctuations. Some case studies showed that the MPC method is effective in achieving a lower power tracking error than the individual control of the HESS. In [94], a multi-level MPC is proposed for OSVs to minimize power tracing error. First level is a non-linear Robust Tube-Based MPC (NRTB-MPC) that is proposed to optimize the propeller shaft speed under environmental disturbances on sea and ship model uncertainties to derive the required propulsion load power. Second level utilizes this load demand to determine the power split between diesel gensets, batteries and UC using MPC approach. However, the performance of this method is not evaluated against any other strategies or benchmark. In [95], NMPC is designed to optimize the time constant of a bandpass filter to achieve power variation smoothing, while maintaining battery temperature and SOC within limits.

Various approaches are investigated to minimize fuel consumption. In [96], NMPC is implemented for an all-electric hybrid ship with DC distribution system, which aims to keep the genset within optimal operating region on the SFOC curve, while maintaining DC grid voltage stability. In [97], QP and mixed integer programming (MIP) are designed based on a known load profile to reduce the fuel consumption, to meet the load demand and to maintain SOC within design range for all-electric hybrid tug operations. From the study, QP is found to be computationally efficient, but the solution includes engine working at a low loading condition, which is fuel inefficient. MIP is then investigated to include control of switching on and off of the

engines. The MIP problem is solved by a genetic algorithm (GA) routine from MATLAB optimization. However, results show an increase in switching of power between the engines as power regulation frequency increases from ten minutes time step to two minutes time step, despite the addition of term to control switching of the engines, which is undesirable in real life application. The work is further extended in [98, 99], where a load estimation method is proposed. A comparison was made to conventional rule-based control strategy and the suggested power management strategy demonstrated 8.9% improvement in the total cost value. However, the result largely depends on the accuracy of the load prediction.

In [100, 101], ECMS is chosen as the power management strategy to investigate the capabilities for fuel reduction of diesel hybrid system with batteries as compared to conventional diesel mechanical propulsion system due to its fast convergence to local minima which makes real-time implementation possible. In [102], the feasibility of ECMS is investigated for all-electric hybrid tug operations with a simulation study. However, for all these studies, there is no benchmark of the fuel savings achieved by ECMS as compared to conventional strategies.

In [103], a multi-scheme is proposed for a hybrid fuel cell driven passenger ship, where according to certain operating conditions, power management switches between classical state-based control, Proportional-Integral (PI) control, heuristics charge depleting charge sustaining (CDCS) control and ECMS. Simulation results show an improvement of hydrogen consumption by using the multi-scheme approach as compared to cases where individual strategies are implemented throughout an eight-hour operation.

2.4.3.3 Ship emission reduction

According to the IMO, ship efficiency is evaluated through the energy efficient design indicator (EEDI) and energy efficiency operation indicator (EEOI) [2, 6]. These two indicators are mainly targeted at the amount of CO₂ produced per ship capacity and transport work. As EEDI is calculated in the design phase based on one operation point, and is limited to bulk carriers, tankers, container and ro-ro vessels, and all-electric ship system is excluded [6]. [104] proposed that EEOI is a more suitable representation of the GHG emissions of the ship during lifetime operation. EEOI is defined as the ratio of mass of CO₂ produced per unit transport work as follows:

$$EEOI = \frac{mCO_2}{transport\ work} \quad (2.12)$$

where mCO_2 is the mass of emitted CO₂.

Optimization-based approach is adopted in [104, 105] for all-electric ship without energy storage device to limit GHG emissions to EEOI limit, where the cost function is formulated as:

$$\min COST = \sum_i COST_i \cdot P_{i,k}^* \cdot FC_i(P_{i,k}^*) + maintenance\ cost \quad (2.13)$$

where $COST_i$ is the fuel cost of i th genset, $P_{i,k}^*$ (kW) is the dispatched power of the i th genset, $FC_i(P_{i,k}^*)$ (gFuel/kWh) is the specific fuel cost, and maintenance cost is defined in [104]. The cost function is subjected to power balance constraints, as well as CO₂ emission constraints:

$$EEOI = \frac{mCO_2}{transport\ work} = \frac{\sum_i c_i \cdot P_i \cdot FC_i(P_i)}{LF \cdot V} \leq EEOI_{m,max} \quad (2.14)$$

where c_i (gCO₂/gFuel) is a conversion factor to convert amount of fuel to CO₂ in grams emitted, P_i (kW) is the power produced by the i th genset, LF is the loading factor calculated based on ship type, V (kn) is the ship average velocity and $EEOI_{m,max}$ is the EEOI limit. The cost function is solved by DP offline. The work is extended in [106, 107] to include energy storage system, which sees a reduction in operation cost and EEOI.

Apart from CO₂, NO_x emissions in particular, is a cause of concern among the ship emissions due to the possible trade-off between NO_x emission and fuel consumption as reported in [1, 19]. However, studies on power management strategies considering NO_x emission are limited. In [108], NO_x emission is considered in the MPC power management approach by adding a NO_x emission constraint. While in [19], it is proposed that NO_x emission reduction is formulated as a control objective instead of a constraint. NO_x emission and fuel consumption are formulated into a multi-optimization problem, solved using Genetic Algorithm (GA), and the resulted pareto front are shown under static load. However, the real-time implementation of these results on physical system are not further discussed. None of the studies in the marine application suggest a method to manage the compromise between NO_x emission and fuel consumption in real-time.

2.5 Summary

In this chapter, an overview of different ship operating system is first introduced. As conventional diesel-mechanical propulsion system struggles to achieve fuel efficient operations for vessels with dynamic load variations such as tugboats and OSVs, ship electrification and hybridization offers solutions to address the challenges of poor fuel efficiency for such vessels. With the increased flexibility of the all-electric hybrid power system, advance control is required to maximize the desired benefits

of the system. Optimization-based methods for HEVs have been widely researched, and DP and ECMS are the two most widely researched method for global optimization and instantaneous optimization methods respectively. DP can achieve global optimal results but is found to be computationally intensive. It is not possible to implement DP in real-time as future information on the load demand is required. Therefore, DP is often used as a benchmark to evaluate the optimality of other power management strategies. ECMS demonstrates significant fuel savings compared to conventional RB strategies and can achieve close to optimal results of DP. In addition, it is real-time implementable. In recent years, predictive approach such as MPC are investigated. The performance of MPC largely depends on the accuracy of the prediction model and tuning of the penalty weights.

Studies for optimization-based power management methods in marine applications are found to begin in the recent years. Unlike HEVs, power management of all-electric hybrid ship system faces a different set of challenges with varying control priorities and requirements with different vessel types, dynamic load conditions that can vary in mega-watts range, and multiple engine control. In naval applications, power management control of naval vessels tends to focus on reducing computational time for optimization routines and predictive approaches to maintain power system stability under high ramp loads to ensure system reliability, redundancy. Approaches to minimize fuel consumption are investigated mainly for commercial vessels. Among the methods that have been investigated, some limitations highlighted include engine working at a low loading condition and frequent switching of the gensets which is undesirable in real life application. In addition, these studies are conducted in simulation and have not been validated on an industrial-based hybrid power system. Studies on power management strategies considering NO_x emission are also limited, and the compromise between NO_x emission and fuel consumption in real-time is not addressed. In this thesis, these research gaps will be addressed in the following chapters.

Chapter 3

Modeling and Validation of All-Electric Hybrid Power System

In this chapter, the laboratory-scale hybrid power system test bed built in NTU mechatronics lab is described in detail. The key components of the hybrid power system are modelled in MATLAB\Simulink. The transient and dynamic response of the simulation models are validated and calibrated against the laboratory-scale test bed, and validation results are presented and discussed.

3.1 Laboratory-scale test bed

A scaled down laboratory hybrid power system test bed is built in NTU mechatronic lab, as shown in Fig. 3.1. The system is designed based on an actual all-electric hybrid tug with a DC distribution system. The main power source includes two synchronous generators driven by prime movers, and Li-ion batteries, connected on the same DC distribution line. The AC power output from the generator is converted to DC through an uncontrolled bridge rectifier. The charging and discharging of the batteries are controlled by the bidirectional DC-DC converter between the batteries module and the DC grid. The energy from the main power sources are supplied to a DC resistor load bank connected at the downstream of the DC distribution. Different loading scenarios can be implemented through the controllable load levels of the DC resistor load bank. The real-time controls of the hybrid power system testbed are implemented through dSPACE DS1103 PPC controller board.

The maximum power of the laboratory hybrid power system is designed at 12kW. For a physical tugboat, the maximum propulsion power can vary over a wide range depending on the type of tugboat, the operation region, vessel speed and other design factors. Taking reference to a 60-65 BPT harbor tugboat with typical maximum propulsion power at 3800kW [15], the maximum power of the laboratory hybrid power system is 0.32% of a physical system, approximately at a scale factor of 1/300. In the following, the system main components, hardware, software controls, and specifications of the equipment will be described in detail.

Figure 3.1 Laboratory-scaled all-electric hybrid power system test bed

3.1.1 Prime movers and brushless synchronous generators

Due to the space and ventilation constraints of the laboratory environment where the test bed is built, the diesel engines are emulated by two Permanent Magnet Synchronous Motors (PMSM) as the prime movers. The PMSM are driven by ABB ACS355 variable frequency inverter, supplied by 3 phase 415VAC power source. The variable frequency inverter takes in analog input of 0-10V for the speed reference of the motor. The speed reference is issued from the dSPACE DS1103 controller board through the D/A output port. A solid shaft incremental encoder with 5000 pulse per revolution (PPR) is connected to the PMSM shaft to measure its rotational speed. The data is collected through the differential RS422 output circuit to the incremental encoder port of the dSPACE DS1103 controller board. The parameters of the PMSM are stated in Table 3.1.

Mechanical power from the motor is converted into electrical AC power output of the brushless synchronous generator. The shafts of the PMSM are mechanically attached to the brushless synchronous generator through flexible couplings, and the setup is shown in Fig. 3.2. The generator is fitted with Automatic Voltage Regulator (AVR) to regulate the 3 phase AC output voltage of the generator. The AVR is a PI type controller. The default reference voltage is the rated output voltage of the generator. Voltage output at the generator stator is fed to the AVR and the controller determines the required excitation current for voltage regulation. Specifications of the generator are stated in Table 3.2.

Table 3.1 Parameters of the PMSM

Model: CDQC TP112M-4-E	
Parameters	Values
Nominal power (kW)	4
Nominal voltage (V)	380
Nominal speed (RPM)	1500
Number of poles	4
Nominal current (A)	8.07

Figure 3.2 PMSM motors and brushless synchronous generator

Table 3.2 Parameters of brushless synchronous generator

Model: MECC ALTE ECP28-1VS/4A	
Parameters	Values
Nominal power (kVA)	7.8
Nominal voltage (V)	400
Nominal speed (RPM)	1500
Number of poles	4
Direct-axis synchronous reactance, x_d	2.02
Direct-axis transient reactance, x_d'	0.175
Direct-axis sub transient reactance, x_d''	0.125
Quadrature-axis synchronous reactance, x_q	0.74
Quadrature-axis sub transient reactance, x_q''	0.26
Transient time constant, T_d'	0.055
Sub transient time constant, T_d''	0.02

3.1.2 Control panels

The variable frequency inverters, power electronics devices, sensors, as well as circuit protection devices are housed within two control cabinets – Motor control cabinet and power electronics and DC bus cabinet.

The motor control cabinet, as shown in Fig. 3.3, mainly consists of variable frequency inverters, motor voltage and current sensors, protection devices such as circuit breakers and isolators, 24V power supply for sensors. The 3 phase 415Vac power supply from the grid enters the cabinet to the inverters, and output to the PMSM. The main control communication to the inverter is through BNC-type connection port for analog signal interface, from digital-to-analog (D/A) converter on dSPACE controller board to the inverters for speed reference control.

Figure 3.3 Motor control cabinet

The power electronics and DC bus cabinet, as shown in Fig. 3.4, mainly consists of diode bridge rectifiers, two 1200 μF smoothing capacitors connected in series, AC and DC voltage and current sensors, DC power supply for the sensors, circuit breakers and isolators. Majority of the power and communication input/output ports are located on this panel. The generator AC output power are fed into the diode bridge rectifiers to convert to DC power output. The DC power output from both generators and DC power from the ESS are connected to the same DC power output to the DC load. Communication ports largely consist of BNC-type connection ports to output analog signal from the AC and DC current and voltage sensors to analog-

to-digital (A/D) converter on the dSPACE controller board for data collection. The single line diagram of both cabinets are in Appendix B.

Figure 3.4 Power electronics and DC bus cabinet

3.1.3 Voltage and current sensors

The location of the current and voltage sensors installed in the system are as indicated in Fig. 3.5. For the ESS, voltage and current sensors are in built with the bidirectional DC-DC converter control.

Figure 3.5 Locations of AC and DC current and voltage sensor

The motor AC input rms current and voltage sensors are purchased off-the-shelves. The specifications of the current sensor and voltage sensor is stated in Fig. 3.6 (a) and (b), respectively.

Figure 3.6 Specifications for motor AC input (a) current sensor (b) voltage sensor

For the generator AC output current and voltage sensors, the custom build sensor board as shown in Fig. 3.7, is modified from previous project in [109] to improve the tolerance level of the measuring resistors for this test bed. The current and voltage

transducers used are LEM HX-10P and LEM LV 25-P, respectively, based on Hall Effect measuring principle. The specifications are shown in Fig. 3.7.

For the AC current measurement, the line current flow directly through the primary coil of the current transducer. For the AC voltage measurement, the primary coil is connected for phase to phase voltage measurements. As the primary coil allows only a small current to flow through, resistor R_1 is added to limit the current input meet the measuring range of the primary coil. The output current from the secondary coil of both transducer is converted to output voltage through the measuring resistor R_L and R_M . Power supplied to the transducer is $\pm 15V$ DC, and analog voltage output measurements are collected using the dSPACE controller board. To ensure full range of signal is measured, the calculation of R_L , R_M and R_1 are done using the maximum value of the measured signal considering the voltage range of the dSPACE A/D converter. The circuit design is shown in Fig. 3.8.

Figure 3.7 Specifications of the generator AC output current and voltage transducers

Figure 3.8 Circuit design of the generator AC output current and voltage sensor board (reproduced from [109])

For DC current measurements, a shunt resistor is placed in series with the line current, and the proportional differential voltage across the shunt resistor is measured. The output voltage from the shunt resistor is amplified for the dSPACE A/D converter. For DC voltage measurements, voltage transducers are purchased off the shelves. Specifications are shown in Fig. 3.9.

Figure 3.9 Specifications of DC current and voltage sensors

3.1.4 Energy storage system

The energy storage system comprises of Lithium ion (Li-ion) batteries and bidirectional DC-DC converter, controllers and protection devices as shown in Fig. 3.10. In this system, there are 3 modules of Li-ion batteries, connected in series. Each battery module consists of 144 Panasonic 18650 battery cells in 12-series-12-parallel (12S12P) configuration. The specifications of the Li-ion battery module are stated in Table 3.3.

The bidirectional DC-DC converter is responsible for the control of charging and discharging currents from the battery. In this system, the converter is customized with separate charging and discharging circuits. The charging circuit limits the charging power at 1.5 kW due to design constraints. Discharging circuit is capable of power and voltage control of 0-4 kW and 0-600 V respectively. One of the limitations of this system is the related low accuracy of the power and voltage control of $\pm 6\%$.

The main control communication is through analog signal interface, to switch between charging and discharging circuit, power and voltage control, as well as obtaining the power and voltage control references. Data transfer from the system to

the dSPACE controller is formatted in RS232 serial communication protocol. The output data includes battery voltage and current measurements, converter output voltage and current measurements, as well as battery SOC. The control circuits are powered by 220 VAC external power source.

Table 3.3 Specifications of Li-ion battery module

Parameters	Values
Nominal voltage (V)	43.2
Fully charged voltage (V)	50.4
Rated capacity (Ah)	34.8
Maximum capacity (Ah)	34.8
Capacity at nominal voltage (Ah)	32.4
Max. Continuous charging/discharging rate	0.2C
Peak charging/discharging rate	1C
Internal resistance (Ω)	0.5

Figure 3.10 Energy storage system

3.1.5 Controllable DC load

The DC load consists of resistors, solid state relays and driver, protective breakers as shown in Fig. 3.11. The resistors of different ratings are arranged in 8 groups, each with a solid-state relay switch. By controlling the relay switches, different load levels can be achieved. The maximum load power of the resistor bank is approximately 10kW at 540VDC, with minimum step load of 1%.

The on/off state of the solid-state relay switches are controlled by a relay driver (ULN 2803A), with digital input from dSPACE digital I/O. The solid-state relay and relay driver is powered by +12VDC power supply. The circuit design of the load is shown in Fig. 3.12.

Figure 3.11 Controllable DC load

For this test bed, the signal interfaces involved for the controls and data acquisition between dSPACE controller and the hybrid power system equipment are summarized in Fig. 3.14.

Figure 3.13 dSPACE controller set up

Figure 3.14 dSPACE controller board signal interfaces

3.2 Modelling of all-electric hybrid power system

3.2.1 Diesel engine and governor

The diesel engine model has been well established in various studies, and the level of complexity of the model depends on the application. In this study, the power system considered adopts the modern DC power distribution, and handling of the reactive power is not necessary. Hence, the engine can be modeled as a first order system with time delay. The diesel engine model described in the following is based on the model used in [31, 111, 112]. The model relates the fuel injection input and output torque of the engine in terms of per unit (p.u.):

$$T_m(s) = e^{-\tau s} \frac{K_y}{1 + \tau_c s} Y(s) \quad (3.1)$$

where $T_m(s)$ is the output torque, K_y is the torque constant, and $Y(s)$ is the fuel index expressed in nominal values from 0 to 1.0 p.u.. The time delay τ and time constant τ_c can be calculated by:

$$\tau \approx \frac{1}{2n_m N} \quad (3.2)$$

$$\tau_c \approx \frac{0.9}{2\pi n_m} \quad (3.3)$$

where n_m is the engine rotational speed (revolution per seconds), and N is the number of engine cylinders.

The mechanical system of the engine translates the output torque to angular motion. Using Newton's second law for rotation, the mechanical system can be represented as:

$$J_{eq} \frac{d\omega_m}{dt} = T_m - T_{em} - \omega_m C_r \quad (3.4)$$

where J_{eq} is the equivalent inertia of the engine shaft, T_{em} is the electromechanical torque of the synchronous generator, ω_m is the angular speed of the engine (rad/s) and C_r is the rotational loss coefficient. An inertia constant, H can be defined, to translate Eq. (3.4) to p.u. expression, where $J_{eq} = 2H$.

The governor is modeled as PI controller to regulate the engine speed based on a given speed reference. For variable speed engines, the speed is adjusted according to the engine loading to achieve better fuel efficiency, based on the SFOC map of the diesel engine given by the engine manufacturers. In actual system, the speed reference is usually pre-determined for each load level and stored in a lookup table for implementation.

3.2.2 Generator and excitation system

The synchronous machine model from the MATLAB\Simulink Simscape Power System library is adapted to present the synchronous generator model. The main governing equations can be found in [113]. The synchronous machine takes the engine rotational speed, as well as generator field voltage as machine input, to generate electrical output. The generator output voltage will depend on the amount of generator field voltage, which is determined by the excitation system. The excitation system of the generator is responsible for the regulation of the generator's output voltage.

The main components of an excitation system are the automatic voltage regulator (AVR) and exciter. In this study, the model used in [111] is adapted where the AVR is modeled as a PI controller and the exciter is represented by a first order system as shown in Fig. 3.15. τ_{ec} and τ_f are the exciter and sensing time constant values allocated as 0.001 and 0.01 according to the model defined in the literature.

The three phase AC voltage output from the generator is converted to DC voltage on the main power distribution line through a rectifier.

Figure 3.15 Block diagram of generator excitation system

3.2.3 Battery

A generic Li-ion battery model is implemented from the MATLAB\Simulink Simscape Power System library. The model parameters are extracted from the battery parameters listed in Table 3.3. The battery voltage for the charging and discharging mode used in the model is defined by [114]:

When $i^* < 0$,

$$E_{\text{charge}} = E_0 - \frac{K \cdot Q}{it + 0.1 \cdot Q} \cdot i^* - \frac{K \cdot Q}{Q - it} \cdot it + Ae^{-B \cdot it} \quad (3.5)$$

When $i^* > 0$,

$$E_{\text{discharge}} = E_0 - \frac{K \cdot Q}{Q - it} \cdot i^* - \frac{K \cdot Q}{Q - it} \cdot it + Ae^{-B \cdot it} \quad (3.6)$$

where E_{charge} and $E_{\text{discharge}}$ are the battery charge and discharge voltage (V) respectively. E_0 is battery constant voltage (V), K is the polarization constant (A/h), Q is the maximum battery capacity (Ah), i^* is the low frequency current dynamics (Ampere) and it is the extracted capacity (Ah), which can be derived from $it = \int i dt$, A is the exponential voltage (V) and B is the exponential capacity (A/h),

which can be obtained from the battery discharge characteristics curve shown in Fig. 3.16. The temperature and aging effects of the battery are not considered.

Figure 3.16 Battery discharging characteristics curve

The SOC of the battery is the measure of the amount of capacity in the battery. In order to maintain the operating life span of the battery, limits on the SOC need to be set so as to prevent over-charging or deep-discharging. The range of SOC where the battery is permitted to vary is referred to as the Depth-of-Discharge (DOD). A widely used method for SOC estimation is the coulomb counting method [115, 116], and SOC can be calculated using:

$$SOC(t) = SOC(t - 1) + \frac{I(t) \cdot \Delta t}{Q_n} \quad (3.7)$$

where Q_n (kWh) is the nominal battery capacity, $SOC(t)$ is the SOC of the battery at time t , $I(t)$ is the amount of discharged current (negative value for charging), and Δt is the time step.

3.2.4 Bidirectional DC-DC converter

The bidirectional DC-DC converter [117], as shown in Fig. 3.17, is necessary when there is bidirectional flow of current, and makes it possible for battery of a lower voltage to be connected to the grid with a higher voltage. The two modes of operation are buck mode and boost mode. In the buck mode, S2 is active, and S1 acts as a diode, stepping down the voltage and allow battery to charge. In the boost mode, S1 is active, and S2 acts as a diode, stepping up voltage output at V_{DC} enabling battery to discharge.

The converter can also implement various control such as voltage mode control and current mode control, which can be achieved through designing of the control circuit to control the pulse width modulation (PWM) of the S1 and S2. Since the exact switching behavior of the converter is not necessary for this system level study of power management control, average value models proposed in [72, 112, 118, 119] are suitable to be implemented. An average value model of the converter with current and voltage control loops adapted from the literature is as shown in Fig.3.18. The switch model is replaced with current/voltage sources, and the converter is assumed to be working in a continuous conduction mode.

The main design parameters of the converter are the inductor and capacitor sizing, calculated based on input and output voltage ratio, maximum current and voltage ripple, as well as switching frequency of the converter[120, 121]:

$$L = \frac{V_{DC}(1-D)}{f_s \Delta i_L} \quad (3.8)$$

$$C_1 = \frac{\Delta i_L}{8f_s \Delta V_{batt}} \quad (3.9)$$

where V_{DC} is the output voltage of the bidirectional DC-DC converter at the DC grid side. ΔV_{batt} (V) is the maximum output voltage ripple of the converter at the battery

side and Δi_L (A) is the maximum current ripple allowed. D is the duty cycle defined as $D = \frac{V_{batt}}{V_{DC}}$, and f_s (Hz) is the switching frequency of S1 and S2. By determining the designed maximum current and voltage ripple, the inductor and capacitor sizing L (H) and C_1 (F) can be calculated.

Figure 3.17 Bidirectional DC-DC converter

Figure 3.18 Average value model of bidirectional DC-DC converter (a) Boost and (b) Buck

3.2.5 Load

The main loads in the ship system is the thruster loads. Auxiliary loads includes hotel and service loads such as lightings, heating, ventilation and air condition (HVAC) etc. In an all-electric hybrid power and propulsion system, the thrusters are connected to the main DC distribution line through electric motors and DC/AC

inverters. Such drive system usually displays a constant load characteristic where the power drawn can remain constant under voltage variations.

Therefore, in this study, the load is modeled as a controlled current source. The power demand of the loading scenarios is converted to current demand based on the DC grid voltage calculated by ohms law:

$$I_{load} = \frac{P_{load}}{V_{DC}} \quad (3.10)$$

where P_{load} (W) is the load demand, V_{DC} (V) is the DC grid voltage and I_{load} (A) is the current reference to the controlled current source.

3.3 Experimental validation and calibration

The main power sources components of the all-electric hybrid power system model are validated against the laboratory-scale hybrid power system test bed.

3.3.1 Genset

The dynamic response of the actual motor-generator set and simulated engine-generator model is investigated under both loaded and unloaded conditions, and results are shown in Fig. 3.19. Under no load condition, a step input from zero to rated speed is applied to the prime mover, and the generator no load DC voltage is measured after the uncontrolled rectifier output. Here, the main objective is to compare the generator voltage rise time and no load voltage under this condition. The engine is assumed a 5 seconds ramp time from zero to rated speed, and hence, PMSM is given a 5 seconds ramp at $t = 10$ s, to generate the actual generator voltage response. From the simulation results as shown in Fig. 3.19 (a) and (b), the simulation model shows close relation to experimental results in terms of transient

rise time, as well as the steady-state generator output voltage. The test bed generator has a system setting that the generator excitation system starts to be active only when generator reached 30% of its rated frequency. Under this limit, generator will not be active. This can explain the 2s time delay in the generator voltage response under ramp speed input observed in Fig. 3.19 (b), and is taken into consideration in the simulation model.

Figure 3.19 (a) Ramp speed input (b) generator no load voltage under ramp speed input (c) Step load input under rated speed (d) generator DC voltage under step load input

A step load is then applied to the generator at rated speed from 25% of the engine rated load, from 1 kW to 4 kW at $t = 15$ s, and back to 1 kW at $t = 25$ s. The main objective is to simulate the voltage droop of the generator across the rectifier, and

calibrate the amount of voltage droop on both the simulation and test bed setup. On the test bed, voltage reference of the AVR is fixed at default rated value. Hence, the voltage reference in simulation is adjusted to match the experimental values, as shown in Fig.3.19 (c) and (d). The deviation of the transient response is mainly due to the tuning of the PI control in the AVR, which can be adjusted.

3.3.2 Energy storage system

A charging and discharging cycle is applied to compare the response between the average value model and actual converters. The converter is operated in voltage control mode. V_{batt} and I_{batt} are measured at the output of the battery modules, and VDC and IDC are measured at the output of the bi-directional dc-dc converter. The results are shown in Fig. 3.20.

The simulation models assume ideal condition where there are no losses across the bi-directional dc-dc converter. Hence in experimental results, due to the losses across the converter during discharge, it is observed that battery discharges at a higher current to achieve the same output current at the converter. Similarly, for charging, current flowing into the battery is lower in experimental results than in simulation, although converter demands slightly more current from the grid.

Comparing the voltage trends, V_{batt} slightly differs between experimental and simulations as a result of the difference in battery current during charging and discharging. Converter reference voltage is set at 540Vdc for both simulation and experiments. In simulation, the converter is in ideal state where PI controller is tuned to maintain output voltage at reference voltage of 540Vdc. While in experiments, due to 5% accuracy range of the converter controller device for voltage control, the obtained output voltage is slightly lower than the reference voltage of 540Vdc. In addition, few instances of large voltages dips were observed when battery changes

from charging to discharging state. This is due to a constraint in the construction of the converter control circuit, where there is a lag-time to switch between the charging and discharging circuit. Due to this limitation in experimental setup, there were rare instances of the sudden mismatch between power supply and demand during the switching lag time where battery is to supply power, resulting in large voltage dip. For example, at $t = 600$, generator 1 received switch off command, while the battery did not discharge immediately due to the lag time in switching circuit, leading to the insufficient power supply to meet the power demand. However, the system was able to recover and continue operation. In the simulation and in real life application on actual system, the bidirectional DC-DC converters are not subjected to such limitation and hence, such performance is not expected.

Figure 3.20 Output voltage and current of battery and bidirectional DC-DC converter

Chapter 4

Equivalent Consumption Minimization Strategy for All-Electric Hybrid Power System¹

In this chapter, the concept of ECMS is first introduced. The power management problem is formulated according to ECMS approach to minimize fuel consumption. A multi-level power management framework is then proposed, to apply the optimization solution to existing power management system. Preliminary studies on the proposed strategy is done through simulation and the real-time implementation is investigated on the laboratory-scale hybrid power system test bed. An improved rule-based strategy is introduced to set as a benchmark to evaluate the performance of the proposed ECMS. Finally, the proposed framework is validated on a full-scale system in a laboratory facility located in MARINTEK, Trondheim. The experimental procedures are illustrated in detail. Finally, the experimental results are presented and discussed.

¹ The main findings of this chapter are presented in:

- Chua, L.W.Y., Tjahjowidodo, T., Seet, G.L., Chan, R., and Ådnanes, A.K. “Equivalent Consumption Minimization Strategy for Hybrid All-Electric Tugboats to Optimize Fuel Savings”, *Proceedings of 2016 American Control Conference*, Boston, MA, pp. 6803-6808, 2016
- Chan, R., Chua, L.W.Y., and Tjahjowidodo, T. “Enabling Technologies for Sustainable All-Electric Hybrid Vessels” (invited paper), *Proceedings of IEEE International Conference on Sustainable Energy Technologies (ICSET)*, Hanoi, Vietnam, pp. 401-406, 2016
- Chua, L.W.Y., Tjahjowidodo, T., Seet, G.G.L., and Chan, R. (2018). “Implementation of Optimization-Based Power Management for All-Electric Hybrid Vessels” *IEEE Access*, 6, 74339-74354, DOI: 10.1109/ACCESS.2018.2883324.

4.1 Equivalent Consumption Strategy

4.1.1 Concept

The formation of a power management problem into an optimization problem requires each decision variable to have an associated cost, and this cost determines if the control objective can be achieved while minimizing the cost function. However, in the case of an all-electric hybrid power system, it is clearly recognizable that the cost of battery energy is not directly comparable to the energy cost of fuel.

The ECMS was first introduced in HEVs applications as a solution to this problem, where an equivalent fuel cost can be associated to the use of battery energy. ECMS assumes a charge sustaining operation, where the amount of battery energy used will be recharged by the engines in the future. Under this assumption, the equivalent cost for the use of battery energy is a positive cost derived by considering the average fuel required to recharge the battery along the energy path from the engine to the battery. A negative cost is associated with charging of the battery, which is equivalent to the fuel consumption when engine is used to provide this amount of energy.

The ECMS considers only instantaneous equivalent fuel cost, and hence it is real-time implementable. Although this approach does not give global optimal solutions by minimizing fuel consumption over the whole operating profile, near optimal results have been demonstrated in HEVs applications in literature. Motivated by the advantages of ECMS, this work develops the power management strategy for an all-electric hybrid power system using this approach. The general system configuration of an all-electric hybrid vessel with DC distribution consisting on n number of engines and batteries is considered, as shown in the schematic diagram in Fig. 4.1. The main control objective of the power management strategy is to minimize fuel consumption. The formulation of the power management optimization problem is illustrated in the next section.

Figure 4.1 Schematic of the system considered in this work

4.1.2 Problem formulation

Using the ECMS concept, the total equivalent fuel cost of the system is determined as a sum of the fuel cost of the engines, and the equivalent fuel cost associated to the batteries energy usage is defined as:

$$C_{total,eqv} = \sum_{i=1}^n C_{eng,i} + C_{batt,eqv} \quad (4.1)$$

Where $C_{total,eqv}$ is the total instantaneous equivalent fuel cost, $\sum_{i=1}^n C_{eng,i}$ is the total instantaneous fuel cost of the n number of engines, and $C_{batt,eqv}$ is the instantaneous equivalent fuel cost associated to batteries energy. The fuel costs are expressed in grams in this study.

Firstly, the fuel cost of the engine is to be determined. The steady-state fuel consumption of the diesel engines can be obtained from the fuel efficiency map of the engine, which can be obtained from the engine manufacturers. From the fuel efficiency maps, the SFOC of the engine can be derived across the engine operating range. An example of the SFOC curve of a 4-stroke high speed diesel engine rated

at 1200 kW is shown in Fig. 4.2, obtained from engine manufacturer's data used in [15].

Figure 4.2 SFOC curve of 4-stroke engine

As seen in the figure, the SFOC of the engine varies across the whole engine operating range. The engine is usually most fuel efficient within 60%-80% of loading, where the SFOC is the lowest. As the engine loading goes under 40%, the SFOC curve increases exponentially. Hence, during ship operations, low engine loading conditions are not desirable.

The variation of engine SFOC across the engine loading have been analyzed in most power management literatures. Most of these presented studies have shown that the variation of engine SFOC across the engine loading can be well approximated by a second order polynomial function expressed as [97, 111, 122]:

$$SFOC(P_{eng}) = a \left(\frac{P_{eng}}{P_{eng,rated}} \right)^2 + b \left(\frac{P_{eng}}{P_{eng,rated}} \right) + c \quad (4.2)$$

where $SFOC(P_{eng})$ (g/kWh) is the SFOC value across the engine loading, P_{eng} (kW) is the engine loading and $P_{eng,rated}$ (kW) is the maximum continuous rating of the

engine, while a , b and c are the coefficients of the fitted polynomial, which can be defined accordingly for each engine SFOC curve. Using the second order polynomial function, the SFOC curve fitted to the engine data is shown in Fig. 4.2. The values of a , b and c are 0.716, -1.016 and 1.322 respectively.

Since ECMS is an instantaneous cost, the fuel cost of each engine is defined as the amount of fuel consumed by the engine within each instant of sampling time interval. This can be determined using the SFOC relationship derived in equation (4.2) as follows:

$$C_{eng,i} = SFOC(P_{eng,i}) \cdot \frac{\Delta t}{3600} \cdot P_{eng,i} \quad (4.3)$$

where $C_{eng,i}$ is the instantaneous fuel consumption within a sampling time interval of i th engine, $P_{eng,i}$ is the i th engine loading, $SFOC(P_{eng,i})$ is the SFOC value at the specific engine loading. Δt is the time interval at which the optimization problem is solved. For two or more gensets operating in parallel, the total instantaneous fuel consumption can be obtained by summing up the individual instantaneous fuel consumption. A scaling factor of 3600 is added to convert Δt from seconds to hour since $SFOC(P_{eng,i})$ is expressed as grams per kilo-watt hours.

The conversion losses from mechanical to electrical energy of the genset is assumed by:

$$P_{eng,i} = \frac{P_{gen,i}}{n_{eng,i}} \quad (4.4)$$

where $n_{eng,i}$ is the conversion losses, and $P_{gen,i}$ is the power output of the i th genset. The total fuel cost of the n engines in the system can be determined by combining Eq. (4.1)-(4.4).

Next, the battery equivalent fuel consumption is defined as:

$$C_{batt,eqv} = s \cdot FC \cdot \frac{\Delta t}{3600} \cdot P_{batt} \quad (4.5)$$

where $C_{batt,eqv}$ is the instantaneous battery fuel cost within a sampling time interval, s is the equivalence factor, FC is a fuel conversion factor, and P_{batt} (kW) is the battery power. Both the equivalence factor and the fuel consumption factor are the key factors of ECMS that will affect the optimization results. The equivalence factor is defined as the train of efficiencies along the power flow between the engine and the batteries, during battery discharging and charging as follows:

When $P_{batt} \geq 0$,

$$s = \frac{n_{batt} \cdot n_{dc/dc}}{n_{eng}} \quad (4.6)$$

When $P_{batt} < 0$,

$$s = \frac{1}{n_{batt} \cdot n_{dc/dc} \cdot n_{eng}} \quad (4.7)$$

where $P_{batt} \geq 0$ represents discharging, and $P_{batt} < 0$ represents charging. n_{batt} and $n_{dc/dc}$ are the battery and bidirectional DC-DC converter efficiencies respectively.

In most references, FC is defined as an average SFOC value of the engines, converting the battery power to an equivalent fuel cost. Comparing the defined fuel cost of engine and equivalent fuel cost of the batteries in Eq. (4.3) and (4.5), it is observed that FC value can directly influence the operating region of the engines. In this study, the aim is to minimize fuel consumption, and it is desirable to maximize the engine operation around the most fuel-efficient operating point, which is the

loading point with the lowest SFOC value. To achieve this condition, FC is defined to be the minimum SFOC value of the engine:

$$FC = \min[SFOC(P_{eng})] \quad (4.8)$$

In this way, engine is encouraged to operate at the minimum SFOC point, since it is slightly cheaper in terms of fuel cost to use the engine than to use the battery at this point. Low engine loading is especially discouraged due to the exponential increase in SFOC value when engine loading falls beyond 40%, which increases the fuel cost of using the engines as compared to equivalent fuel cost of using the batteries. A similar method has also been proposed in [100] with the control objective to operate engine with the minimum SFOC.

Finally, the optimization problem is defined as:

$$\min J = C_{total,eqv} \quad (4.9)$$

To ensure the match between the power demand and the supply, the following condition, presented in the form of an equality constraint, has to be met:

$$P_{load} = \sum_{i=1}^n P_{gen,i} + P_{batt} \cdot n_{batt} \cdot n_{dc} \quad (4.10)$$

where P_{load} (kW) is the total load demand considering propulsion loads, hotel and service loads.

In addition, inequality constraints are also implemented to preserve the battery lifetime as designed:

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \quad (4.11)$$

where $SOC(t)$ can be derived from Eq. (3.7), SOC_{min} and SOC_{max} is the minimum and maximum SOC limit of the battery, as well as considering the operating

envelope of gensets and the maximum charging/discharging rates of the batteries as follows:

$$P_{eng,i_min} \leq \frac{P_{gen,i}}{n_{eng,i}} \leq P_{eng,i_max} \quad (4.12)$$

$$P_{batt_min} \leq P_{batt} \leq P_{batt_max} \quad (4.13)$$

where P_{eng,i_min} and P_{eng,i_max} are the minimum and maximum rating of each of the engines. P_{batt_min} is a negative value representing the maximum power when battery charges at maximum rate, and P_{batt_max} is a positive value representing the maximum power when battery discharges at maximum rate.

The optimization problem can be classified as a nonlinear constrained optimization problem. An interior point method can be used to solve this type of problem. In this study, the interior point method is implemented by using *fmincon* nonlinear programming solver in MATLAB\Simulink optimization toolbox.

A few assumptions were taken in the problem formulation as follows:

1. The power management problem considers the fuel consumption at steady-state values. Fuel consumption during engine ramping is not considered.
2. The losses through engine-generator coupling, propulsion drive-trains, as well as efficiencies of the battery during charging/discharging and bi-directional DC-DC converter are assumed to be constant.

4.2 Multi-level power management framework

4.2.1 Overview of the framework

In order to implement the solution from the proposed ECMS, a multi-level power management framework is proposed, as shown in Fig. 4.3. The framework consists

of two main levels. The primary level represents the existing fundamental power management control in the system, where voltage droop functionalities, load dependent start/stop rules and protection controls are executed. This level also takes care of the main communications and control between the drives, field controllers and the power system components, which are the main functions of existing industrial power management control system.

The proposed ECMS is implemented on the supervisory level, where power reference values are generated and sent to the primary level control. The reason for implementing the proposed strategy on the supervisory level instead of enforcing it on the primary control level, is to be able to integrate the optimized solution to any existing industrial power management control system. In addition, with this general framework, any further development in optimal power management strategies can be implemented to an existing industrial system, not limited to this approach.

Figure 4.3 Overview of proposed multi-level power management framework

4.2.2 Control methodology

At every time step, the optimization problem is solved to determine the power allocation between the gensets and the battery. The solution consisting of the amount of power to be delivered by each power source, is sent to the primary control as reference values for each power source. Slight adaptations are required on the primary level to control the system according to the power references. The control philosophy is as follows:

For genset controls,

- When $P_{G,ref}^* = 0$, genset is offline.
- When $P_{G,ref}^* > 0$, genset will be switched on. Primary level controls will take over the genset control to determine the ω^* and V_{set}^* values during operation.
- When more than one genset are operating in parallel, the gensets will share the load according to voltage droop control that exists in most industrial based power management control.

For energy storage system controls:

- When $P_{batt,ref}^* \geq 0$, battery is in discharging mode. In this mode, bidirectional DC-DC converter can be in voltage or power control mode, depending on the system state. When battery is discharging in parallel with working gensets, the converter will be in power control mode to deliver the amount of power according to the battery power reference. The voltage on the DC distribution line is maintained by the genset. However, when all gensets are offline, battery is the only source of power. Battery will be in the voltage control mode to maintain the voltage stability on the DC distribution

grid during load variations. The amount of discharging current will vary according to the amount drawn by the load demand, which should also coincide with battery power reference generated from the supervisory control.

- When $P_{batt,ref}^* < 0$, battery will be in charging mode. The converter will only operate in power control mode, as at least one genset will be operating to provide excess power for battery charging. Therefore, the converter will draw power to charge the battery according to the battery power reference from the supervisory control.

4.3 Simulation case studies

The feasibility of the proposed ECMS approach and the multi-level power management framework is first investigated on dynamic models of the hybrid power system developed in Simulink. A case study over the operation of a 60-65 Bollard Pull Tonnes (BPT) harbor tugboat consisting of two gensets and batteries is considered. The main modes of operations can be broadly categorized as (i) transit, (ii) standby or idle, and (iii) ship assist operation. A representative time-domain load profile of the harbor tugs derived based on field engine data and experiences of tug owners is obtained from [15] and used in this case study, as shown in Fig. 4.4. The system parameters are illustrated in Table 4.1.

Figure 4.4 Harbor tug operation duration and time-domain load profile for simulation case study

Table 4.1 System parameters

Parameters	Symbols	Values
Maximum propulsion power	$P_{load,max}$	3800 kW
Generator rated power	$P_{gen1_max}, P_{gen2_max}$	1200 kW
SFOC @ 100% engine power	SFOC	211 g/kWh
Battery capacity	Q	520kWh
Maximum charging rate	C_{batt_min}	2C
Maximum discharge rate	C_{batt_max}	3C
Depth-of-discharge	DOD	0.6
Generator efficiency	$\eta_{gen,1}, \eta_{gen,2}$	0.965
Battery efficiency	η_{batt}	0.98
Bidirectional DC-DC converter	$\eta_{dc/dc}$	0.98
Drivetrain efficiency	η_{dt}	0.945

4.3.1 Conventional RB vs proposed ECMS – Proof of concept

To proof the concept of the proposed ECMS approach, the cost function of the proposed equivalent consumption formulation was solved at a sample time of 10 s, and the numerical results of the optimized power split between the power sources were compared to the RB solution used in [7, 15]. The simulation results are presented in Fig. 4.5, and the fuel consumption of the ECMS approach is compared against RB solution in Fig. 4.6.

With RB approach, the operation of the gensets and batteries follows the pre-set rules as shown in Fig. 4.5 (a). During standby mode, batteries are used to provide for the load demand and both gensets are not operating. During transit mode, genset 1 is switched on and supply for the average load demand and power fluctuations are passed to the battery. During the ship assist operation load demand reaches its peak, both gensets are switched on, and battery power is also used to provide for the peak power. Genset 1 mostly operates around 90% loading, and battery capacity remains more than 80% throughout the operation cycle.

With the proposed ECMS approach, a more fuel-efficient operation is achieved. Although the operation pattern of genset 1 is similar to the RB approach, the ECMS approach manage to maintain the genset loading at around 75%-80% instead, which is around the most fuel-efficient operating range of the engine as seen in the SFOC curve in Fig. 4.2. The operation time of genset 2 is reduced, where it is switched on for a short duration of about 4 mins during the ship assist operation. The SOC of the battery is well maintained within the SOC limit of 30% to 90%.

With the optimal loading of the engine and better utilization of the battery power, the proposed ECMS demonstrated a fuel savings of up to 14.3%, as shown in Table 4.2. A comparison of the fuel consumption in time-domain as shown in Fig. 4.6 (a) shows that the proposed approach achieves a more significant amount of fuel savings

during the ship assist operation. This is most likely due to the maintaining operating range of genset 1 around the efficient point, as well as the reduced running time of genset 2 with the utilization of battery power.

For a fair comparison of the total fuel consumption based on the same amount of energy used, the amount of battery capacity remaining at the end of the operation cycle has to be considered. In Fig. 4.6 (b), it can be seen that battery SOC is about 51% at the end of the operation cycle in the proposed ECMS approach, while the battery SOC remains at 90% at the end of the operation with the RB approach. If the engine is charging the battery to its original SOC at the optimal loading, this will require an additional 41.9 kg of fuel. However, the gross fuel savings, not considering this amount of fuel that is required to charge the battery, may be valid in this case considering that shore power is available to charge the batteries, since batteries need not be recharged by the engine eventually. This amount of energy can be supplied by the shore power when the vessel is berthed, which is one of the main benefits of having an all-electric hybrid power system for tugboats. In this case, the proposed ECMS maximized the utilization of shore power, which will result in emission reduction and total fuel cost savings, since shore power is cheaper and emission free.

Table 4.2 Fuel consumption of RB vs ECMS

	Fuel (kg)	Savings (%)	ΔSOC
RB	293.4	-	0
ECMS (with shore charging)	251.4	14.3%	0.39

Figure 4.5 Simulation results of (a) RB and (b) Proposed ECMS

Figure 4.6 Simulation results comparing (a) Fuel consumption and (b) Battery SOC

4.3.2 Improved RB strategy

From the simulation results, the advantage of ECMS over RB in terms of fuel savings has been shown. To take a step deeper in evaluating the performance of the proposed strategy, an improved RB strategy is formulated by utilizing the trends of operations from the optimized solution of the proposed strategy. The aim of the improved RB strategy is to set a higher benchmark to the proposed strategy for the experimental validation on the actual system. The improved RB strategy determines the power allocation among the power sources based on a pre-defined load level to start the genset, as well as considering the battery SOC condition. For the same system consisting of two gensets and batteries as main power sources, the cases of operation generated by the refined operation rules are described in pseudo code as follows:

For $P_{load} \leq P_{G1,on}$,

Case 1, $SOC \leq SOC_{min}$,

$$P_{G1} = P_{G1,opt}, P_{G2} = 0, P_{batt} = P_{load} - P_{G1}$$

If $|P_{batt}| > |P_{charge,max}|$,

$$P_{batt} = P_{charge,max}, P_{G1} = P_{load} - P_{batt}$$

Case 2, $SOC_{min} < SOC < SOC_{max}$,

$$P_{G1} = 0, P_{G2} = 0, P_{batt} = P_{load}$$

If $|P_{batt}| > |P_{discharge,max}|$,

$$P_{batt} = P_{discharge,max}, P_{G1} = P_{load} - P_{batt}$$

Case 3, $SOC \geq SOC_{max}$

$$P_{G1} = 0, P_{G2} = 0, P_{batt} = P_{load}$$

If $|P_{batt}| > |P_{discharge,max}|$,

$$P_{batt} = P_{discharge,max}, P_{G1} = P_{load} - P_{batt}$$

For $P_{G1,on} < P_{load} \leq P_{G1,opt}$,

Case 4, $SOC \leq SOC_{min}$,

$$P_{G1} = P_{G1,opt}, P_{G2} = 0, P_{batt} = P_{load} - P_{G1}$$

$$\text{If } |P_{batt}| > |P_{charge,max}|,$$

$$P_{batt} = P_{charge,max}, P_{G1} = P_{load} - P_{batt}$$

Case 5, $SOC_{min} < SOC < SOC_{max}$,

$$P_{G1} = P_{G1,opt}, P_{G2} = 0, P_{batt} = P_{load} - P_{G1}$$

$$\text{If } |P_{batt}| > |P_{charge,max}|,$$

$$P_{batt} = P_{charge,max}, P_{G1} = P_{load} - P_{batt}$$

Case 6, $SOC \geq SOC_{max}$,

$$P_{G1} = P_{load}, P_{G2} = 0, P_{batt} = 0$$

For $P_{G1,opt} < P_{load} \leq P_{G1,opt} + P_{G2,opt}$,

Case 7, $SOC \leq SOC_{min}$,

$$P_{G1} = P_{G1,opt}, P_{G2} = P_{G2,opt}, P_{batt} = P_{load} - P_{G1} - P_{G2}$$

$$\text{If } |P_{batt}| > |P_{charge,max}|,$$

$$P_{batt} = P_{charge,max}, P_{G1} = P_{G1,opt}, P_{G2} = P_{load} - P_{G1} - P_{batt}$$

Case 8, $SOC_{min} < SOC < SOC_{max}$,

$$P_{G1} = P_{G1,opt}, P_{G2} = P_{G2,opt}, P_{batt} = P_{load} - P_{G1} - P_{G2}$$

$$\text{If } |P_{batt}| > |P_{charge,max}|,$$

$$P_{batt} = P_{charge,max}, P_{G1} = P_{G1,opt}, P_{G2} = P_{load} - P_{G1} - P_{batt}$$

Case 9, $SOC \geq SOC_{max}$,

$$P_{G1} = \frac{P_{load}}{2}, P_{G2} = \frac{P_{load}}{2}, P_{batt} = 0$$

For $P_{load} > P_{G1,opt} + P_{G2,opt}$,

Case 10, $SOC \leq SOC_{min}$,

$$P_{G1} = \frac{P_{load}}{2}, P_{G2} = \frac{P_{load}}{2}, P_{batt} = 0$$

Case 11, $SOC_{min} < SOC < SOC_{max}$,

$$P_{G1} = P_{G1,opt}, P_{G2} = P_{G2,opt}, P_{batt} = P_{load} - P_{G1} - P_{G2}$$

$$\text{If } |P_{\text{batt}}| > |P_{\text{discharge,max}}|,$$

$$P_{\text{batt}} = P_{\text{discharge,max}}$$

Case 12, $\text{SOC} \geq \text{SOC}_{\text{max}}$,

$$P_{G1} = P_{G1,\text{opt}}, P_{G2} = P_{G2,\text{opt}}, P_{\text{batt}} = P_{\text{load}} - P_{G1} - P_{G2}$$

$$\text{If } |P_{\text{batt}}| > |P_{\text{discharge,max}}|,$$

$$P_{\text{batt}} = P_{\text{discharge,max}}$$

The improved RB strategy will be used as the new benchmark to the performance of proposed strategy, in the experimental validations on the actual system in the next following sections.

4.4 Preliminary experimental investigations on laboratory-scale test bed

In this preliminary experimental investigation, there are three main objectives to be achieved. The first objective is to validate the feasibility of the proposed multi-level power management framework for real-time application. This can be demonstrated by observing the relation between the power references from the supervisory level and the actual power delivered by the power sources during operation. In addition, voltage stability of the system has to be maintained. Second objective is to evaluate the performance of ECMS against the improved RB strategy. Final objective is to validate the accuracy of the simulation studies on the hybrid power system simulation model, through comparing the system steady-state and transient response of the simulation and experimental results during operation. An accurate hybrid power system simulation model can be used as a platform for future power management studies and development.

4.4.1 Case study

The same case study of a harbor tug operation is investigated. However, the duration of the operation cycle is reduced by ten times for the feasibility of laboratory test-bed validation. The detailed breakdown of the operation and the reduced duration and the respective time-domain load profile is shown in Fig 4.7. In this case study, the maximum propulsion load is set at 8 kW, according to the range of operation of the DC load bank in the test bed system. Other system parameters are set according to the ratings of the test bed components, summarized in Table 4.3.

Table 4.3 System parameters for laboratory-scale hybrid power system test bed

Parameters	Symbols	Values
Maximum propulsion power	$P_{load,max}$	8 kW
Generator rated power	$P_{gen1,max}, P_{gen2,max}$	4 kW
SFOC @ 100% engine power	SFOC	211 g/kWh
Battery nominal capacity	Q	4.5kWh
Maximum charging rate	$P_{batt,min}$	1.5kW
Maximum discharge rate	$P_{batt,max}$	4kW
Depth-of-discharge	DOD	0.6
Generator efficiency	$\eta_{gen,1}, \eta_{gen,2}$	0.965
Battery efficiency	η_{batt}	0.96
Bidirectional DC-DC converter	$\eta_{dc/dc}$	0.98
Drivetrain efficiency	η_{dt}	0.945

Figure 4.7 Harbor tug operation duration and time-domain load profile for laboratory-scale test bed case study

4.4.2 Results and Discussions

The DC voltage on the main DC distribution grid is shown in Fig. 4.8. From both simulation and experimental results, DC voltage is well maintained between 510-550VDC, within 6% of voltage droop, when the proposed framework is implemented with both ECMS and improved rule-based strategy. In simulation, the maximum voltage peaks and dips fall within the acceptable range of 10% throughout the operation cycle. During experiments, a few instances of large voltages dips are observed, which is within expectation, due to the known limitation of the bidirectional DC-DC converter control. The switching lag-time between the charging and discharging circuit resulted in temporal loss of power supply to meet the load demand, as explained in earlier chapters. However, the test bed system is able to recover quickly from the voltage dip and resume back to normal operating conditions as soon as battery starts to discharge.

Comparing the simulation and experimental results in terms of power split control in Fig. 4.9, firstly, the feasibility of the proposed framework is well demonstrated. In both simulation and experiment, the actual power delivered by the generator and battery closely follows the ideal power references from the supervisory level.

The performance of ECMS is as shown in Fig. 4.9 (a). As expected, both genset 1 and 2 are maintained near optimal operating point of about 60%-80% loading when switched on. During transiting mode, battery operates in charging mode to increase the engine load to improve fuel efficiency. Genset 2 is switched on during the ship assist operation where load demand is high and shares the load equally with genset 1. The improved RB strategy works as well as the proposed ECMS. The power allocation is almost similar to the solution from the proposed strategy as shown in Fig. 4.9 (b), hence demonstrating equivalent fuel consumption.

Although fuel savings are not demonstrated, there are a few additional points to be highlighted which proposed strategy may have an advantage over RB strategies. Firstly, it is worthy to note that designing of the power management rules to cover all cases of operations is a tedious process. In this particular system with three main power sources, improved RB strategy consists of 12 different case scenarios as illustrated earlier. It can be expected that the number of scenarios and complexity in the designing of the RB logic will increase exponentially with additional power sources. Whereas, for the proposed strategy, the problem formulation can be easier extended to n number of gensets, and is easily adaptable to include more power sources, as compared to the RB method. Secondly, solution of the proposed strategy is generated based on numerical computations, which can achieve near optimal results. While the performance of the RB methods depends on multiple decision factors, such as load levels to start the genset and optimal genset loading, which are decided based on experience. Therefore, the RB methods may not guarantee similar

performance as the ECMS under other loading scenarios, which can be further validated in the final experimental validation on a different system setup.

The case study also further validated the accuracy of the simulation model of the hybrid power system to reflect the actual system response. Similar transient and steady state responses are observed between the simulation and experimental results. Hence, the simulation model of the hybrid power system can be used as the platform for preliminary studies on further developments of the power management strategies before real-time execution on actual system, or in cases where real-time experiments are not possible.

Figure 4.8 Simulation vs experimental DC voltage on main distribution line (a) Proposed ECMS (b) Improved RB

Figure 4.9 Simulation vs experimental results of (a) Proposed ECMS (b) Improved RB

4.5 Experimental Validation on Full-Scale Ship System

With the feasibility of the proposed framework on the laboratory-scaled hybrid power system testbed, the performance of the proposed framework is implemented on an actual system as shown in Fig.4.10. The facility is located at ABB collaborated hybrid power laboratory in MARINTEK, at the Norwegian University of Science and Technology (NTNU), Trondheim.

The main objective of the final validation is firstly, to validate the proposed strategy and implementation framework on a full-scale system close to an actual vessel power system, with industrial based controllers and power management system. Secondly, to compare the performance of proposed strategy to the improved RB, to validate the potential advantages of the proposed strategy over RB methods.

4.5.1 MARINTEK hybrid power laboratory

The system layout at the MARINTEK hybrid power laboratory is designed based on a full-scale hybrid all-electric vessel with ABB's Onboard DC GridTM, controlled with ABB's Power and Energy Management System (PEMS). The system comprises two high speed diesel engines with variable speed generator sets and an energy storage system with battery bank and capacitor bank, connected to a DC distribution system. The system has two electric motors connected to an eddy current brake to simulate loading scenarios of the power system. The capacitor bank is not used in this study, and the specifications of the rest of the components are as follows:

- Diesel engines:
 - DE1: Perkins 1306C, 209 kWb, 1500 rpm
 - DE2: Perkins 2506C, 412 kWb, 1500 rpm
- Generators:
 - G1: 230 kVA, 50 Hz, 4 poles, 1500 rpm
 - G2: 400 kVA, 50 Hz, 4 poles, 1500 rpm

- Battery:
 - Li-ion batteries: 130 Ah, 346 V, peak charging/discharging: 200 A/400 A, maximum continuous charging/discharging: 100 A/200 A
- Electric motors:
 - M1, M2: 160 kW, 50 Hz, 4 poles

Figure 4.10 MARINTEK hybrid power laboratory

4.5.2 Control interface

The control model of the proposed strategies is developed in Simulink. The signal flow between the control model of the proposed strategy developed in Simulink and the actual system are shown in Fig. 4.11. The control model is first compiled into Dynamic Link Library (.dll) application and loaded to the ABB control interface platform. The ABB control interface platform forms a communication link with the ABB PEMS to access control signals and data transfer. The main control and

communication with the PLC controllers of the power system components are through ABB PEMS.

The multi-level power management framework is implemented as illustrated in Fig. 4.11. Supervisory control signals from the proposed strategy include on/off signal for genset, and power/voltage control of the bidirectional DC-DC converter for battery charging/discharging. Primary power management system controls such as engine governor speed reference, generator AVR voltage reference, voltage droop control for parallel gensets, protection and blackout prevention are according to ABB PEMS.

To simulate the loading scenarios of the experimental case study, the operation profile is converted to torque and speed references for the eddy current brakes and motor drives respectively. The reference signals are sent from the ABB platform to the motor drive units at each defined time step.

Lastly, the system responses are recorded through information collected from ABB PEMS and motor drive units.

Figure 4.11 Implemented multi-level power management framework, signal flow and control interfaces

4.5.3 Case study

Similarly, the harbor tugboat operation is investigated in this experiment. The duration and the total load demand is adjusted to fit the experiments. Firstly, duration is adjusted to 35 minutes, for a closer representation to the duration of an actual tug operation. Also, the maximum propulsion is adjusted to 150 kW to investigate in cases where overall load is relatively low as compared to the design rating of the main power sources. The system parameters are summarized in Table 4.4.

Table 4.4 System parameters for MARINTEK hybrid power laboratory

Parameters	Symbols	Values
Maximum propulsion power	$P_{load,max}$	150 kW
Generator rated power	$P_{gen1_max}, P_{gen2_max}$	300 kW, 120 kW
SFOC @ 100% engine power	SFOC	211 g/kWh
Battery nominal capacity	Q	45kWh
Maximum charging rate	P_{batt_min}	34.6kW
Maximum discharge rate	P_{batt_max}	69.2kW
Depth-of-discharge	DOD	0.6
Generator efficiency	$\eta_{gen,1}, \eta_{gen,2}$	0.965
Battery efficiency	η_{batt}	0.96
Bidirectional DC-DC converter	η_{dcdc}	0.98
Drivetrain efficiency	η_{dt}	0.945

Due to limitations on the lab setup, the experimental procedure is modified to cater to the need for manually starting of the gensets, while minimizing the impact on the results. The tug operation cycle is executed separately in 3 segments. Segment 1 from 0-12 minutes of the cycle consisting of transit and standby operations, segment 2 from 12-23 minutes of the cycle consisting of transit, short standby and ship assist

operations, and segment 3 from 23-35 minutes of the cycle consisting of mainly transit. The detailed breakdown of the operation in each segment is illustrated in Table 4.5. At the start of each segment, the number of required gensets pre-determined from simulation is switched on and remain online throughout the segment. Each segment can be repeated if necessary, without the need to repeat the whole operation. The performance of the proposed framework with both improved rule-based and ECMS are investigated.

Table 4.5 Harbor tug operation duration for experimental validation in MARINTEK

Segment	Operation	Duration (mins)
1	Standby	1.5
	Transit	4.5
	Standby	6
2	Standby	1.5
	Transit (follow ship)	3
	Standby	1.25
	Ship assist	0.75
	Standby	1
	Ship assist	0.75
	Ship assist	1
	Ship assist	0.75
	Standby	1
3	Standby	2
	Transit (Return to port)	5

4.5.4 Results and discussions

The proposed framework is successfully implemented as demonstrated by the results shown in Fig. 4.12. Firstly, the voltage on the DC grid is well maintained between 540-580Vdc, within 6% of voltage droop. One main attribute to the stable voltage is that genset 2 is online throughout the operation cycle, which maintained the DC grid

voltage through voltage droop control in the PEMS. Secondly, the multi-level power management framework is validated. The power references from the proposed ECMS are achieved in the actual power split between the power sources in experimental results. The battery power reference is achieved by operating the bi-directional DC-DC converter in power control mode throughout the cycle. Genset 2 provides the remaining required power in the system, which coincides with the generator power reference. It is observed that the total power delivered to the load is slightly less than the total power delivered by the power sources, due to power transmission losses in the system. Lastly, the SOC of the battery is well kept within the SOC limit of 30% to 90%. The SOC of the battery are not necessarily continuous between the segments since the segments are run separately.

Comparing the performance of proposed ECMS against the improved RB strategy in Fig. 4.13, both strategies shows similar performances in segment 1. The advantage of ECMS over the improved RB is shown in segment 2 and 3. In segment 2, genset 2 is used to provide the required power from the load, as well as charging the battery in the transiting period, based on the improved rule-based strategy. ECMS in this case, utilizes available battery power during this transiting period, since the SOC of the battery is within the SOC limit. Subsequently, as the load demand during ship assist operation is higher than the maximum discharge power of the battery, both ECMS and the rule-based strategy utilize genset 2 to supply for the load demand. However, since the load demand is lower than the optimal operating region of the engine, loading is increased by charging the battery, to avoid low engine loading. In segment 3, where the load demand is similar to the transiting period in segment 2, same trend is observed where the improved rule-based utilizes both genset 2 and battery to provide power for the load, while ECMS utilizes the available battery power. Since the combined installed power of genset 2 and battery are sufficient to provide for 100% of the maximum propulsion power, genset 1 is not utilized throughout the operation. Battery power is better utilized under the proposed ECMS

strategy in segments 2 and 3, which contributes to the overall fuel savings. The fuel consumption in each segment and amount of battery energy used, represented by the change in SOC, is illustrated in Table 4.6. The total fuel consumption is derived by adding the fuel consumption across all 3 segments, while the overall change in SOC is derived by consolidating the change in SOC in each segment.

The proposed ECMS achieved in a substantial amount of fuel savings of up to 24.4% over improved RB strategy, as shown in Table 4.6. Although it is arguable that net fuel savings should be compared based on the same amount of energy used, and hence the battery discharged energy should be accounted for when considering the overall fuel savings. However, the validations are done on a harbor tugboat case study with the option to access to shore power when the vessel is berthed, which can be used to charge the batteries. Therefore, the gross fuel savings, not considering the final SOC of the battery, may represent the actual fuel savings that can be achieved in the presence of shore charging since batteries need not be recharged by the engines eventually.

Some effects on the experimental results that should be noted, due to the system limitation that requires manual start/stop for genset controls. Firstly, the genset remains in idle mode even when it is not utilized, resulting in additional fuel consumed, affecting the overall fuel savings. Secondly, the actual time delay in starting of the genset may not have been fully captured, since genset starts from idle mode, instead of starting up when genset is switched off. This may affect the transient response of the batteries, as batteries provide the transient power required to maintain the system voltage during the genset ramp time.

Nevertheless, this experimental validation demonstrates that the proposed ECMS can adapt and perform under different system parameters and loading conditions. Whereas, the RB methods may show good performance when operation rules are designed based on optimized solutions on a set of system parameters and loading

scenarios but may not perform well when these parameters and conditions are changed. These findings are aligned with the advantages of the proposed strategy over RB methods as seen in the preliminary experimental investigations on the laboratory-scale test bed.

Table 4.6 Fuel consumption of improved RB vs ECMS (MARINTEK)

Segments	Approach	Fuel (kg)	Savings (%)	ΔSOC
Segment 1	Improved RB	1.833	-	0.07
	ECMS	1.833	-	0.07
Segment 2	Improved RB	2.629	-	0.1
	ECMS	2.131	-	-0.4
Segment 3	Improved RB	1.674	-	0.11
	ECMS	0.675	-	-0.16
Total	Improved RB	6.136	-	0.28
	ECMS	4.639	24.4	-0.13

Figure 4.12 Experimental results of ECMS (a) Segment 1 (b) Segment 2 (c) Segment 3

Figure 4.13 Experimental results of improved RB (a) Segment 1 (b) Segment 2 (c) Segment 3

Chapter 5

Multi-Objective Power Management to Reduce Fuel Consumption and Emission

In this chapter, the proposed ECMS is enhanced to consider both fuel consumption and emissions. A novel method to design the equivalent cost and the use of weighting factor is proposed to manage the compromise between fuel efficiency and NO_x emission reduction. The feasibility of the proposed approach is demonstrated through case studies over harbor tugboat operations. Simulation results are presented and discussed.

5.1 Diesel engine emissions

During combustion process, marine diesel engine emission largely comprises nitrogen, oxygen, carbon dioxide, and water vapor with smaller quantities of carbon monoxide, oxides of Sulphur and nitrogen, hydrocarbons and particulate matters (N_2 , CO_2 , CO , NO_x , SO_x , HC, PM). The quantity of the emission are likely to be different during steady state and transient modes of operations, while the composition will remain similar. In this study, only steady state emissions are considered, in line with the IMO emission control standards and regulations.

Among the emissions, there has been stricter regulations in place on CO_2 , NO_x and SO_x due to the relatively high composition among the emissions and their detrimental impacts on the environment and human health. An example of these exhaust gas emission comparison is obtained from [1], for a S50ME-GI Mark 8 Tier II engine for Heavy Fuel Oil (HFO) operation. The engine CO_2 , NO_x and SO_x

emissions data are shown Table 5.1, and the emission trends are plotted across the engine operation load as shown in Fig. 5.1.

Table 5.1 Emissions data of S50ME-GI Mark 8 with HFO operations (Obtained from [1])

Load (%)	SFOC (g/kWh)	CO ₂ (g/kWh)	SO _x (g/kWh)	NO _x (g/kWh)
35	174.6	572	12.22	14.4
40	172.9	567	12.10	14.4
45	171.4	562	12.00	14.4
50	170.0	557	11.90	14.5
55	168.8	553	11.82	14.5
60	167.8	550	11.75	14.6
65	167.0	547	11.69	14.7
70	166.6	546	11.66	14.7
75	166.7	546	11.67	14.7
80	167.0	547	11.69	14.6
85	167.6	549	11.73	14.5
90	168.4	552	11.79	14.2
95	169.4	555	11.86	13.9
100	170.6	559	11.94	13.5

CO₂ is proportional to the amount of fuel consumed, and hence reducing fuel consumption will reduce the amount of CO₂ emissions. According to IMO standards, the amount of emitted CO₂ can be calculated by multiplying fuel consumption with the fuel specific emission rate for the specific type of fuel used:

- Heavy fuel oil (HFO): 3.114 tons of CO₂ / tons of oil consumed

- Light fuel oil (LFO): 3.151 tons of CO₂ / tons of oil consumed
- Diesel oil: 3.206 tons of CO₂ / tons of oil consumed

Figure 5.1 SFOC and emission trends of S50ME-GI Mark 8 Tier II engine (Obtained from [1])

For SO_x emissions, the relationship between sulphur emission and sulphur content is shown to be proportional. Stricter regulations are imposed to limit the SO_x emissions in the coming years. To reduce SO_x, lower sulphur content oil can be used, which is more expensive. An alternative solution to the expensive fuel is the scrubber technology, which reduces the sulphur content through a series of chemical processes.

For NO_x emission, it can be observed from the emission data that there is an increase in NO_x emission when the fuel consumption is low i.e. in the range of 0.6 to 0.9 p.u. load. This trade-off relationship is also highlighted in [19, 100], which poses some challenges in emission control. The emission rate depends on different factors such as fuel types, engine types, engine speed, etc. Currently in the industry, common

methods for NO_x emission control and reduction are the Exhaust Gas Recirculation (EGR) and Selective Catalytic Reduction (SCR). EGR is a proven method that can reduce up to 84% of NO_x emissions from marine engines, enabling a Tier I engine to meet the Tier III NO_x requirements [1]. The percentage of NO_x reduction with EGR depends on the ratio of re-circulating gas. An increase in the recirculating gas will increase the reduction in NO_x emission. However, it is found to increase the fuel consumption as well in some cases. Also, EGR system consumes about 2% of the total main engine power, which increases the fuel consumption indirectly by this amount [1]. While SCR is also capable of achieving up to 95% NO_x reduction, additional storage space for ammonia or urea, which is the main catalytic agent for SCR, is required. For vessels with limited machinery spaces such as tugboats, space might be a constraint for this solution.

Hence, in this study, the possibility to optimize NO_x emission reduction and fuel consumption during engine operation, through the power management control approach, is investigated.

5.2 ECMS approach for NO_x emission reduction

Two SFOC and NO_x emission data across the engine loading is obtained from [1] and [19] respectively. Unlike the SFOC curve, there has not been a known polynomial that can well represent the NO_x emission across the engine loadings. In this study, it is assumed that the NO_x emission can be fitted with a polynomial approximation. However, it should be noted that this polynomial expression should not be assume for all NO_x emission trends across the engine loadings, as there is insufficient data to show that all NO_x emissions follow the same emission trend at the current stage. Hence, the engine emission map should always be considered first

to obtain the emission data of each specific engine and analyzed for an appropriate approximation.

In this study, a third polynomial shows an appropriate fit for both sets of emission data, analyzed through a residual plot as shown in Fig 5.2, as well as goodness-of-fit statistics. The residuals measure the difference between the actual data and fitted data. From the residuals plot, it is shown that the residuals are randomly scattered around zero, which represents that the polynomial model is appropriate to describe the set of data. The root mean square error is 0.2927 and 0.02842, respectively, for case 1 and case 2, which represents that the data are close to the fitted curve.

The SFOC and NO_x data and the fitted curve are shown in Fig 5.3. SFOC curve follows the second order polynomial approximation as stated in Eq. (4.2). Different NO_x emission trends were observed between both engines. Case 1 follows a convex curve as shown in Fig. 5.3 (a), with the lowest specific NO_x emission when engine is operating between 30%-50% load. While case 2 display a closer relation to a concave curve as shown in Fig. 5.3 (b), with most emission inefficient region around 60%-80% loading and specific NO_x emission reduces when engine load increases beyond 80% loading. Both cases will be used to evaluate the performance and effectiveness of the proposed approach.

Figure 5.2 3rd order polynomial fit and residuals plot

(a)

(b)

Figure 5.3 SFOC (labelled on the left axis) and SNOX (labelled on the right axis) of (a) PERKINS 2506C (Case 1) (b) MAN S50ME-GI (Case 2)

Hence, the specific NO_x emission can be expressed as:

$$SNOX_1(P_{eng}) = w_1 \left(\frac{P_{eng}}{P_{eng,rated}} \right)^3 + x_1 \left(\frac{P_{eng}}{P_{eng,rated}} \right)^2 + y_1 \left(\frac{P_{eng}}{P_{eng,rated}} \right) + z_1 \quad (5.1)$$

$$SNOX_2(P_{eng}) = w_2 \left(\frac{P_{eng}}{P_{eng,rated}} \right)^3 + x_2 \left(\frac{P_{eng}}{P_{eng,rated}} \right)^2 + y_2 \left(\frac{P_{eng}}{P_{eng,rated}} \right) + z_2 \quad (5.2)$$

Where $SNOX_1(P_{eng})$ and $SNOX_2(P_{eng})$ is the specific NO_x emission of engine; w_1 , x_1 , y_1 , z_1 and w_2 , x_2 , y_2 , z_2 are the coefficient of the third order polynomial approximation for case 1 and 2 respectively.

The polynomial coefficients of the specific NO_x emission and the specific fuel consumption data are obtained from MATLAB curve fitting *polyfit* function as listed in Table 5.2 and Table 5.3. a_1, b_1, c_1 and a_2, b_2, c_2 are the coefficients of the second order polynomial approximation of the SFOC for case 1 and 2 respectively, according to Eq. (4.2).

Table 5.2 Polynomial coefficients for SFOC₁ and SNOX₁

a₁	b₁	c₁	w₁	x₁	y₁	z₁
36.55	-86.94	252.8	-2.564	22.49	-16.89	10.63

Table 5.3 Polynomial coefficient for SFOC₂ and SNOX₂

a₂	b₂	c₂	w₂	x₂	y₂	z₂
54.62	-80.91	196.2	-18.81	31.01	-15.58	16.86

Using this expression, a similar ECMS approach can be used to consider NO_x emission cost. The main control objective is to reduce NO_x emission. Applying the same concept of the earlier proposed approach, the engine is encouraged to operate around the lowest emission region, at the $SNOX_{m,min}(P_{eng,i})$ point, to minimize the emission during operation. The fuel cost terms are replaced with NO_x emission cost, and the minimization problem can be formulated as:

$$\begin{aligned} \min H = & \sum_{i=1}^n [SNOX_m(P_{eng,i}) \cdot P_{eng,i}] \\ & + s \cdot SNOX_{m,min}(P_{eng,i}) \cdot P_{batt} \end{aligned} \quad (5.3)$$

Similarly, the optimization problem can be classified as a nonlinear constrained optimization problem, which can be solved by interior point method using *fmincon*

algorithm in MATLAB. The numerical solution is presented through the same harbor tugboat case study and the simulation results are presented in Fig 5.4-5.9.

5.2.1 Simulation studies – Case 1

The numerical solution of Eq. (5.3) in the case of the 60-65BPT harbor tug operation is shown in Fig. 5.4 (a). A comparative case of pure fuel reduction is also simulated and the numerical solution according to cost function in Eq. (4.9) is shown in Fig. 5.4 (b). Both cases assume the batteries are fully charged to the upper limit of 90% before the start of the operation.

As observed from the results, using the proposed approach modified for NO_x emission reduction, engine loading is maintained at around 40% when engine is operating, which is at the engine's lowest specific NO_x emission. Since each engine is kept at 40% loading, both engines are switched on for transit operation, and the excess power is charged to the battery. Only during ship assist operation, both engines increased to 100% of the power with battery assistance, in order to meet the load demand. The SOC are well kept within the limits of 30% to 90%, while meeting the load demand. Whereas, for the case of fuel reduction, the most fuel-efficient range of this engine model is at the full load, as shown in the SFOC curve in Fig. 5.3 (a). Hence, it is observed that engine 1 operates near the rated power most of the time through the operation cycle, and the excessive power are charged to the battery. Engine 2 is required to operate only during ship assist operation. Battery power is used less in this case, since the engines are able to provide most of the power of the load demand while operating at the rated power.

Figure 5.4 Numerical solutions of (a) NO_x emission minimization (b) Fuel consumption minimization with PERKINS 2506C engine (Case 1)

The average specific NO_x emission and specific fuel consumption, as well as the total amount of NO_x emission and fuel consumed over one harbor tug operation cycle are compared. The effect of the NO_x emission reduction on fuel consumption can be observed in Fig. 5.5. Using the proposed strategy on NO_x emission reduction, the average specific NO_x emission is reduced from 13.24 g/kWh to 7.527 g/kWh. However, this increased the average SFOC from 197.3 g/kWh to 220.7 g/kWh. The increase in fuel consumption is expected as the SFOC is high at low engine loading, and in this case the engine loading is maintained at fuel inefficiency range of 40% load to minimize the NO_x emission.

To have a fair comparison of the fuel consumption of both cases, the fuel consumption should be compared for the same amount of energy used. Hence, the net amount of battery energy consumed is considered by assuming:

$$\begin{aligned} & \text{Fuel consumed (corrected)} \\ &= \text{Actual fuel consumed} + \frac{\Delta SOC \cdot Q_n \cdot SFOC_{avg}}{10^3} \end{aligned} \quad (5.4)$$

where ΔSOC is the difference between initial SOC and final SOC, Q_n (kWh) is the battery nominal capacity and $SFOC_{avg}$ (g/kWh) is the average SFOC over one operation cycle. As seen from Fig. 5.6, the reduction in specific NO_x emission resulted in an increased in fuel consumed from 280.5 kg to 315.1 kg.

Figure 5.5 Comparison of average SFOC vs SNOX over one harbor tug operation cycle (Case 1)

Figure 5.6 Comparison of average SNOX and fuel consumed (corrected) over one harbor tug operation cycle (Case 1)

5.2.2 Simulation studies – Case 2

Similarly, for case 2, the case of the 60-65BPT harbor tug operation is shown in Fig. 5.7. In this case, using the proposed approach modified for NO_x emission reduction, the engine loading should maintain near rated load, which is the most efficient operating point with lowest specific NO_x emission, as shown in Fig. 5.3. However, the NO_x emission curve for case 2 has a combination of convex and concave nature, resulting in an inflexion point at around 40% engine load. This resulted in more than one local minima in the optimization problem. While solving the optimization using interior point method, solutions may end up at either local minimum point, hence resulting in the slight fluctuation in genset loading. This is observed in the numerical solution in Fig. 5.7 (a), where the solution tends to fluctuate between 40% and 100% loading during the ship assist mode of operation. This is a known constraint when solving nonlinear problems with the interior point method and tuning of a suitable search starting point may help to improve the results. In this study, repeated trials are conducted to solve the minimization problem on different starting point and the starting point that results in the least fluctuation is adopted. Nevertheless, the overall average specific NO_x emission of 13.69 g/kWh is achieved using the approach, which is close to the minimum specific NO_x emission for this engine. Other optimization techniques can be further explored to overcome this challenge in future studies.

For the case of fuel reduction, the engine loading maintains around the efficient operating region of 70%-80% engine load. Engine 2 operation duration throughout the cycle is much lesser than the case of NO_x emission reduction, since engine 1 operates at a higher loading, which is sufficient to provide for the load demand.

Figure 5.7 Numerical solutions of (a) NO_x emission minimization (b) Fuel consumption minimization with PERKINS 2506C engine (Case 2)

The average specific NO_x emission and specific fuel consumption, as well as the total amount of NO_x emission and fuel consumed over one harbor tug operation cycle are compared in Fig. 5.8 and 5.9. Using the proposed strategy on NO_x emission reduction, the average specific NO_x emission is reduced by 3.2%, as compared to the case with pure fuel reduction control. Similar trend is observed where this reduction in NO_x emission resulted in an increase in fuel consumption. Using the same method to account for the corrected fuel consumption, it can be observed that a 3.2% of reduction in specific NO_x emission leads to a 3.6% increase in fuel consumption. It may be observed that the NO_x emission reduction is relatively small as compared to

that in case 1, as the maximum and minimum specific NO_x emission of the engine in case 2 varies over a small range.

Figure 5.8 Comparison of average SFOC vs SNOX over one harbor tug operation cycle (Case 2)

Figure 5.9 Comparison of average SNOX and fuel consumed (corrected) over one harbor tug operation cycle (Case 2)

Both the engine fuel consumption and emission trends reflect the trade-off in fuel consumption as a result of the reduction in NO_x emission. Therefore, a method is proposed to manage this compromise within the two extreme cases of pure NO_x emission and pure fuel reduction. The proposed method is based on the concept of ECMS approach, described in the following section.

5.3 ECMS approach to manage fuel consumption and NO_x reduction

To manage the increase in fuel consumption due to the effects of NO_x emission, a method to define the equivalent cost for engines and the batteries is proposed, based on ECMS approach, combined with the use of control weighting K_{NOX} that defines the amount of priority given to NO_x emission reduction. The proposed cost function formulation is expressed as:

$$\min G = \sum_{i=1}^n [\Phi \cdot P_{eng,i}] + \Omega \cdot s \cdot P_{batt} \quad (5.5)$$

$$\Phi = \left[(1 - K_{NOX}) \cdot \frac{SFOC_m(P_{eng,i})}{SFOC_{m,base}(P_{eng,i})} + K_{NOX} \cdot \frac{SNOX_m(P_{eng,i})}{SNOX_{m,base}(P_{eng,i})} \right] \quad (5.6)$$

$$\Omega = \left[\begin{aligned} &(1 - K_{NOX}) \cdot \frac{\min[SFOC_m(P_{eng,i})]}{SFOC_{m,base}(P_{eng,i})} \\ &+ K_{NOX} \cdot \frac{\min[SNOX_m(P_{eng,i})]}{SNOX_{m,base}(P_{eng,i})} \end{aligned} \right] \quad (5.7)$$

As $SFOC_m(P_{eng,i})$ and $SNOX_m(P_{eng,i})$ are on a different scale of comparison, the values are normalized against a base value. In this study, the base values $SFOC_{m,base}(P_{eng,i})$ and $SNOX_{m,base}(P_{eng,i})$ are the values at engine rated power where $\frac{P_{eng}}{P_{eng,rated}} = 1$. The cost function is subjected to the constraints in Eq. (4.8) - (4.11).

The value of K_{NOX} is in the range of 0 to 1, where 0 indicates pure fuel consumption minimization case, and 1 indicates pure NO_x emission reduction case. The aim of this approach is to achieve the flexibility to manage the compromise in fuel consumption while reducing NO_x emission, by prioritizing between fuel efficient and emission efficient operation. For example, when a vessel is operating near the harbor or in ECAs where the limit for NO_x emission is more stringent, a pure NO_x

emission reduction control can be adopted. In cases when there are less requirements on the emission reduction, fuel consumption can be improved by adjusting the K_{NOX} to a lower value.

The proposed approach is first investigated for a specific load point at $K_{NOX} = 0.2$, assuming a load demand of 1000 kW, and battery SOC at 90% as a proof of concept. The fuel consumption and emission of case 1 is used. Since battery SOC is at the maximum limit, only battery discharge is feasible in this specific scenario. The function value of Eq. (5.5) over all possible load combinations of both gensets and battery is shown in Fig. 5.10 (a). As observed in this figure, the resulting function value is the lowest in the region where the battery power is zero, and the power demand is shared between the gensets.

From previous study, it is understood that it is more fuel efficient to share the load equally between both gensets in some cases. To investigate in the optimal power split of the gensets in this case, the function value of Eq. (5.5) over all possible genset load combinations is shown in Fig. 5.10(b). As observed from the figure, splitting the load equally between the gensets results in a lower function value. The most optimal power split in this instant is therefore to supply 500 kW from each genset.

When Eq. (5.5) is solved using interior point method from *fmincon* solver in MATLAB, the resulting power split obtained from the numerical solution is:

$$x = [P_{gen,1} \quad P_{gen,2} \quad P_{batt} \quad SOC] = [529 \quad 529 \quad 0 \quad 0.9] \quad (5.8)$$

This solution coincides with the solution obtained from Fig. 5.10(a) and (b), hence showing that the proposed formulation solved using interior point method is able to generate the minimum solution at each instant.

Figure 5.10 (a) Function values of each solution generated from all possible load combinations of gensets and battery and (b) Function values over all possible genset load combinations

The proposed approach is then investigated across the values of K_{NOX} in constant interval of 0.2, over the same case study of harbor tug operation for both engine emission in case 1 and 2.

5.3.1 Simulation studies – Case 1

The numerical solutions of Eq. (5.5) over the range of K_{NOX} , applied over the harbor tug operation cycle, are shown in Fig. 5.11. The average specific NO_x emission as well as fuel consumption at each interval of K_{NOX} are shown in Fig. 5.12.

From the simulation results in Fig. 5.11, it can be observed that under slight influence of NO_x emission cost, where $K_{NOX} = 0.2$, the engine loading is throughout the operation lowered to close to 50%-70%, instead of maintaining at near rated engine power in the case of pure fuel reduction ($K_{NOX} = 0$). A shift in the operating range of the engine closer to the efficient emission point reduces the specific NO_x emission

from 13.2 g/kWh to 8.6 g/kWh, as shown in Fig. 5.12. This reduction is approximately 34.8%, at the expense of 8.7% increase in fuel consumption. As the K_{NOX} value increases from 0.4 to 0.8, engine loadings are shifted towards the emission efficient operating range.

Overall, from the results in Fig. 5.12, the proposed approach performs as expected where the increase in the weighting factor K_{NOX} reflects a reduction in NO_x emission. Significant reduction in NO_x reduction was observed from $K_{NOX} = 0$ to $K_{NOX} = 0.4$, while minimal reduction was achieved from $K_{NOX} = 0.4$ to $K_{NOX} = 1.0$. In this range of K_{NOX} , the power allocation and operating duration of power sources show similar trends in Fig. 5.11, which resulted in similar average NO_x emission and fuel consumption.

From the cost function point of view, this result can be explained by Φ_1 characteristics as shown in Fig. 5.13. Φ_1 is the resulting equivalent cost of using the engines, from combination of fuel and emission. Therefore, when minimizing the cost function, solution will tend towards the minimum point of Φ_1 to determine the optimal engine loading. It can be observed from Fig. 5.13 for $K_{NOX} = 0$ to $K_{NOX} = 0.4$, this minimum point occurs at different engine loading. However, for $K_{NOX} = 0.4$ to $K_{NOX} = 1.0$, the minimum points are within a small range of engine loading of within 10%, which resulted in similar numerical solutions.

Therefore, in this case, adjusting K_{NOX} values between 0 to 0.4 will offer a significantly effect in the prioritizing between emission and fuel reduction. Beyond this range, the effects can be expected to be more gradual.

Figure 5.11 Numerical solutions of power split for different KNOX values (Case 1)

Figure 5.12 Effects of increasing KNOX values on NO_x emission and fuel consumption (Case 1)

Figure 5.13 Φ_1 characteristics

5.3.2 Simulation studies – Case 2

Solving the optimization problem for case 2 faces some challenges, due to the mixture of convex and concave nature of the NO_x emission curve, as explained earlier. In this case, when Ω_2 is formulated using $\text{SNOX}_{m.min}(P_{eng,i})$, repeated tuning of search starting point could not obtain feasible results. Hence, Ω_2 is slightly increased by replacing $\text{SNOX}_{m.min}(P_{eng,i})$ with the the specific NO_x emission value at the next efficient range of 90% engine load. The simulation results of this are shown in Fig. 5.14 and Fig.5.15.

From Fig. 5.14, it can be seen that most of the numerical solutions across the values of K_{NOX} often fluctuates between 40% and 100% engine loading, due to the presence of the inflexion point of the specific NO_x emission curve, at around 40% engine load. This characteristic is reflected in Φ_2 as shown in Fig. 5.16, which affected the optimization solutions.

The effects of varying K_{NOX} on NO_x emission and fuel consumption is shown in Fig. 5.15. It can be observed that the increase in weighting factor led to an overall reduction in NO_x emission and increase in fuel consumption for each unit of energy produced (kWh). However, there is slight inconsistency in the NO_x emission reduction with the increase in control weighting from $K_{NOX} = 0$ to $K_{NOX} = 0.4$. An increase in K_{NOX} does not display a continuous decreasing trend NO_x emission as intended. Instead, the increase in control weighting from $K_{NOX} = 0$ to $K_{NOX} = 0.2$ led to a large reduction in NO_x emission, following by an increase in NO_x emission again when control weighting increase from $K_{NOX} = 0.2$ to $K_{NOX} = 0.4$. This inconsistency in continuous reduction in NO_x emission could be a result of the mentioned difficulty in solving nonlinear optimization problem with multiple local minima points. The repeated fluctuations of genset loading, often between 40% and 100% loading as observed in Fig. 5.11, may be a reason to the discrepancy in the continuous reduction

of NO_x emission with increasing control weighting. Nevertheless, a gradual reduction in NO_x emission can be achieved by increasing control weighting from $K_{\text{NOX}} = 0.4$ to $K_{\text{NOX}} = 1.0$.

Figure 5.14 Numerical solutions of power split for different KNOX values (Case 2)

Figure 5.15 Effects of increasing KNOX values on NO_x emission and fuel consumption (Case 2)

Figure 5.16 ϕ_2 characteristics

5.3.3 Discussion of results

From the simulation studies, it is observed that the proposed strategy attempts to achieve the control objective of prioritizing NO_x emission or fuel consumption by shifting the engine operating range closer to the NO_x emission efficient operating range or the fuel-efficient operating range. The prioritization is controlled using the control weighting factor. A weighting factor closer to $K_{NOX}=1$ will shift engine operation closer to the efficient point that minimizing NO_x emission, while a weighting factor closer to $K_{NOX}=0$ will shift the engine operation closer to the fuel-efficient operating range. As expected, the reduction in NO_x emission will result in an increase in fuel consumption as a trade-off.

The case studies on two different engines provided further insights on the performance of the proposed strategies. In case 1, for each unit of energy produced (kWh), the increase in weighting from $K_{NOX}=0$ to $K_{NOX}=0.4$ led to a significant reduction in NO_x emission and increase in fuel consumption. Beyond $K_{NOX}=0.4$, further increase in the weighting factor have minimal effects on the overall NO_x emission and fuel consumption. In case 2, though slight discrepancy in the performance of the proposed strategy is observed, expected behavior could still be obtained to control the prioritization of fuel consumption and emission reduction by varying K_{NOX} values ideally within 0.4 to 1.0.

Overall, the proposed strategy demonstrated the possibility to optimize NO_x emission and fuel consumption through the power management control approach. The proposed strategy allows ship operators to control the reduction of NO_x emission over fuel consumption depending on the requirements of the operating region. For example, greater priority on NO_x emission can be implemented by increasing the control weighting ECAs with stricter emission control. The limitation of the proposed strategy is observed in case 2, where the challenge in solving nonlinear optimization problem with multiple local minima in this case may not allow the

proposed strategy to perform as expected at certain range of the control weighting values. Future studies can look into other optimization methods to overcome this limitation.

Chapter 6

Optimization-based Power Management for Jack-up Rigs Operations

In this chapter, the proposed ECMS approach is adapted for jack-up rigs operations. The proposed ECMS is modified to include charge sustaining operations. The feasibility of the proposed strategy for this application is evaluated over a case study of a section of the draw works operations. Simulation results are presented and discussed.

6.1 Overview of jack-up rigs operations

In the field of offshore oil and gas explorations, one of the types of offshore drilling unit is the jack-up rigs. Jack-up rigs are self-elevating units, capable of raising its platform hull over the surface of the sea waters. The legs of the rig are extended below the hull and into the seabed, to anchor the rig. The number of legs in jack-up rigs designs can vary in the range of 3-8. An example of a jack-up rig is shown in Fig. 6.1, featuring the Maersk Giant, which is one of the ultra-harsh environment jack-up rigs series in Maersk Drilling's fleet [123]. This rig is designed to cope the weather conditions around the year for operations in the North Sea in water depth up to 107m. The legs of the jack-up rig can extend 132m below the hull of the rig.

The main components for drilling are electric drive motors (top drives), drill bit and long drill string that connects the drive motor to the drill head under the seabed for drilling operations to extract oil and gas from under the seabed. Due to the sea waves, the relative distance between the rig and the drill head fluctuates along with the

waves, changing the length of the drill string. Therefore, in order to maintain a control over the length of the drill string, an active heave compensation is required. Active draw works control is responsible for the active heave compensation, where the electric winch is controlled to raise or lower the drill string accordingly, to maintain a constant relative distance between the rig and the drill head. The drill string is made of steel, usually in segments of 15m, with a span of 10-12km long [124]. Hence, a lot of energy is involved in lowering and raising the drill string. Large regenerative power generated during lowering of the drill strings are dumped to a braking chopper, which dissipates the energy as heat to the surrounding seawaters. Harnessing and storing this power could make drilling more efficient and conserve energy.

Another key operation of the draw works is the tripping operation, which involves raising or lowering of the whole stretch of drill string, usually for maintenance purpose to change the drill head or portions of the drill string. This operation involves a repetitive set of actions which are automated. During raising of the drill string, one segment of the drill string is lifted at a time, disconnected from the hook, stacked and the hook is lowered to connect to the next segment of the drill string. During lowering of the draw string, one segment is connected at a time, lowered, then disconnected from the hook and the hook is hoisted up to connect to the next segment. The repeating variations of electrical load demand from the draw works motor from this operation can be challenging for the genset as it tends to involve rapid load changes. An example of the drilling components and draw works are shown in Fig 6.2.

Figure 6.1 Maersk Giant (Image from [123])

Figure 6.2 Main drilling components and draw works (Reproduced from [125])

6.2 An all-electric hybrid power system for jack-up rigs

Majority of the jack-up rigs power systems are conventional AC distribution system. With the advantages of DC distribution system shown on all-electric hybrid vessels with low and medium voltage power system, DC distribution for jack-up rigs low voltage power systems is a new trend to be explored. Modern DC distribution topology can also ease the installation of energy storage such as batteries.

In addition, the installation of energy storage can also provide several benefits for jack-up rig operations. Firstly, energy storage devices with much faster response time can be used to smooth out the load on the generators during drilling operations, as well as reducing the stress on the engines during tripping operations. Secondly, battery can be properly sized to harness some of the regenerative power that are dumped to the breaking resistors during active heave compensations, hence making drilling process more energy efficient, and can also reduce the size of breaking resistors.

Furthermore, for jack-up operations, it is common to keep additional gensets in idle mode, to ensure that the gensets are able to handle sudden load increases. Energy storage can hence be used as the buffer to handle sudden load increase, reducing the number of genset running in idle mode. These can further contribute to the stability of the power system and result in lower fuel consumption and emission.

The single line diagram of an all-electric hybrid power system with DC distribution is shown in Fig. 6.3.

Figure 6.3 Single line diagram of an all-electric hybrid power system with DC distribution for jack-up rigs

6.3 ECMS approach for all-electric hybrid jack-up rigs with DC distribution

To explore the full fuel savings potential of an all-electric hybrid power system for jack-up rigs, the ECMS approach is adapted to optimize the power split between gensets and energy storage.

In this study, the main power sources of the all-electric hybrid power system consist of 4 gensets and batteries, while the main control objective is to reduce fuel consumption. Since the proposed ECMS approach can be applied for n number of engines, the same cost function can be used for this power management problem. However, unlike vessels, such as harbor tugs, where shore charging option is available for the battery, jack-up rigs are usually located far away from shores, and battery can only be charged by the power sources on the rigs. Therefore, the ECMS

approach is enhanced to include charge sustaining function to manage the battery capacity.

To implement charge sustaining control, a penalty function is added to the equivalent fuel cost of the battery, and the cost function is formulated as:

$$\min K = \sum_{i=1}^n \left(\frac{SFOC(P_{gen,i})}{SFOC_{base}} \cdot \frac{P_{gen,i}}{n_{gen,i}} \right) + \alpha_{soc} \cdot \frac{SFOC_{min}}{SFOC_{base}} \cdot s \cdot P_{batt} \quad (6.1)$$

subjected to the same set of constraints described in equation (4.8) to (4.11). Here, the specific fuel consumption is normalized against a base value. The base value is defined as the SFOC value at rated engine power. α_{soc} is the penalty function which is commonly implemented for HEVs applications for charge sustaining control [126], which can be defined as follows:

$$\alpha_{soc} = 1 - \left(\frac{SOC(t) - SOC_{target}}{(SOC_{max} - SOC_{min}) \cdot \gamma} \right)^\beta \quad (6.2)$$

where $SOC(t)$ is the battery SOC at current time step, SOC_{target} is a target value where battery power can be used without penalty. β and γ are variables that define the penalty function. A suitable set of β and γ is tuned for this study such that the SOC is maintained in the desired range, as shown in Fig 6.4.

Figure 6.4 Charge sustaining penalty function

6.4 Case study - Draw works tripping operations

The performance of the proposed approach is investigated through a case study on the tripping operations, for raising of the drill string from the seabed. The operation load profile is a representative profile derived based on understanding and technical advice from the industry on the jack-up rig operation, as shown in Fig. 6.5. The set of repetitive actions to raise each segment of the draw string during tripping is reflected in the load profile, where similar repeated load cycle is observed. Duration of each cycle takes about 3 minutes. Depending on the length of the drill string, tripping operation can last for numerous hours, with breaks and pauses during the operation, as seen in the operation data recorded. For this case study, 10 cycles of tripping operation are investigated. Each cycle reflects the physical operation of raising 1 segment of drill string from the seabed. The system parameters are summarized in Table 6.1.

Table 6.1 Parameters for jack-up rig case study

Parameters	Symbols	Values
Maximum tripping load	$P_{load,max}$	2574 kW
Generator rated power	$P_{gen1_max} \dots P_{gen4_max}$	1720 kW
SFOC @ 100% engine power	SFOC	211 g/kWh
Battery nominal capacity	Q	500 kWh
Maximum charging rate	P_{batt_min}	1500kW
Maximum discharge rate	P_{batt_max}	1500kW
Depth-of-discharge	DOD	0.6
Generator efficiency	$\eta_{gen,1}, \eta_{gen,2}$	0.965
Battery efficiency	η_{batt}	0.96
Bidirectional DC-DC converter	η_{dcdc}	0.98
Drivetrain efficiency	η_{dt}	0.945

Figure 6.5 Draw works tripping operation load cycles

6.5 Results and discussions

The effect of charge sustaining control through the proposed approach is illustrated in Fig. 6.6. In Fig 6.6 (a), while charge sustaining control was not implemented, the engine operates around the fuel-efficient range of about 70%-80% engine load. Excess power is charged to the battery. At the same time, regenerative power from the tripping operations are also absorbed by the battery. In this case, the regenerative power is within the charging limit of the battery, and hence, this amount of free energy can be fully absorbed. As the battery approaches the maximum SOC limit of 0.9, genset is switched off and battery power is used to supply the load demand. The amount of regenerative power that can be absorbed is now limited, since the battery cannot charge beyond the limit. Additional regenerative energy has to be dumped to the braking chopper to dissipate as heat.

Whereas, with charge sustaining control, the SOC of the battery is maintained around the target range of 50%-70% as shown in Fig. 6.6 (b). As SOC approaches the target range, it can be observed that genset power starts to decrease to reduce the charging of the battery. Battery SOC is then maintained within the target range throughout the cycle. This prevents battery from over discharging, hence ensuring available battery power to sustain the system during sudden power spikes. Also, it avoids over charging of the battery, which allows the battery to absorb regenerative energy.

It is interesting to note that in this case study, the load of the tripping operation is relatively small compared to the total installed capacity of the system. In addition, fast response time of batteries can supply for the high ramp load during the tripping cycles. Therefore, it is observed that only 1 genset is utilized to supply for the load demand through the operation cycles.

Figure 6.6 Simulation results of ECMS approach for jack-up rigs (a) Without charge sustaining (b) With charge sustaining

Chapter 7

Conclusion and Future Work

In the final chapter, the major findings and main contributions of this work are elaborated, and some recommendations of future work are discussed.

7.1 Conclusion

This thesis deals with the power management problem of an advanced power system in maritime industries, in particular, the optimal power allocation problem of an all-electric hybrid power and propulsion system with DC distribution, to improve fuel efficiency and reduce emission. To understand the power system response, an all-electric hybrid power system model is first formulated, and a laboratory-scaled hybrid power system is built to validate and calibrate the model.

To determine the optimal power-split between the power sources, an instantaneous optimization-based approach is proposed, which adopts the equivalent consumption minimization strategy. The proposed strategy is validated on an industrial-based full-scale hybrid power system and the performance of the proposed strategy was compared against that of the conventional rule-based strategy used in the industry, demonstrating substantial improvements in fuel savings.

Subsequently, the proposed strategy is enhanced in two areas. Firstly, the proposed strategy is extended to include emission control, where a novel method is proposed to manage the compromise between NO_x emission and fuel consumption. Secondly, the proposed strategy is enhanced with charge sustaining control for the operation of jack-up rigs.

The findings in this thesis are believed to significantly contribute to the understanding of power management in an all-electric hybrid power system and to the development of optimization-based power management control strategies for advanced marine power systems, to improve fuel efficiency and reduce emissions. In the following, the main findings are further elaborated.

Equivalent consumption strategy for all-electric hybrid vessels to reduce fuel consumption

Based on the literature studies in power management of hybrid electric vehicles, the equivalent consumption minimization strategy is identified to be an instantaneous optimization-based approach, which is capable of obtaining near optimal solutions. Motivated by the good performance of this approach, the concept is adopted to formulate an equivalent consumption strategy for the all-electric hybrid power system of marine vessels.

A multi-level power management framework is proposed for real-time practical implementation of the optimized power split solution from the proposed strategy. The solution from the proposed strategy is implemented as supervisory power references, to the existing local power management control system. Future developments in power management strategies can be implemented to an existing industrial system through this general framework, not limited to the proposed strategy.

The initial simulation study is conducted over a harbor tug operation, to prove the concept of the proposed equivalent consumption strategy. It is shown that the proposed strategy is capable of achieving up to 14.3% of fuel savings as compared to the conventional rule-based strategy used in the industry. To further evaluate the performance of the proposed strategy and to validate the advantages over RB approaches, an improved rule-based strategy is designed based on the power

allocation trend of the optimized solution, to set as a new benchmark for experimental validation.

The proposed strategy is successfully implemented using the multi-level power management framework on an industrial-based full-scale hybrid power system with industrial controllers and power management system, designed to replicate an actual all-electric hybrid tugboat. Experimental results show that the proposed strategy achieve up to 24.4% of fuel saving against the improved rule-based strategy. This shows that the design rules that are optimal for one system may not be optimal when system parameters and load condition changes. Whereas, the proposed equivalent consumption strategy is able to adapt and perform under different system parameters and load conditions to achieve fuel savings.

Enhanced equivalent consumption approach to reduce NO_x emission

With the successful implementation of the proposed equivalent consumption strategy on an actual system, the proposed strategy is extended to include NO_x emission control, which is not usually addressed through the power management approach for all-electric hybrid vessels. When power management problem considers only NO_x emission reduction, a reduction in NO_x emission at the expense of the increased fuel consumption is observed, when compared to earlier cases considering only fuel consumption.

To consider both fuel consumption and NO_x emission, a novel method to design the equivalent cost with the use of weighting factor is proposed to manage the influence of NO_x emission cost on the solution. In general, the proposed method yields satisfactory results. Using this method, the emphasis on NO_x emission reduction can be controlled by adjusting the weighting factor.

However, a limitation is observed due to a known constraint when solving nonlinear problems with the interior point method, such that the performance of the proposed

approach largely depends on the properties of the specific NO_x emission curve. When a specific NO_x emission curve consists of both concave and convex properties, the solution of the nonlinear optimization problem tends to be trapped at the inflexion point, and the proposed approach can only perform in a limited range of weighting factor. In cases where the specific NO_x emission curve displays convex properties, the intended results of the proposed method can be achieved.

Optimization-based power management strategy for jack-up rigs applications

As the all-electric hybrid power system with DC distribution is a new trend to be explored for jack-up rigs, the proposed equivalent consumption strategy is investigated for jack-up rig applications. The proposed strategy is easily extended to consider four gensets for this application, in addition to energy storage devices, hence showing that the strategy is not limited to all-electric hybrid vessels.

Due to the geographical location of the rigs which are usually offshore, shore power is not available for battery charging. Hence, the proposed strategy is enhanced with charge sustaining control. Implementation of the charge sustaining control shows a better control over the battery capacity, while ensuring fuel efficient operation. The SOC of the battery is maintained within the targeted range, which prevents the battery from over-charging or over-discharging. Hence, the required battery capacity can be planned and reserved in advance according to the needs of different jack-up operations to achieve an energy efficient operation.

7.2 Main contributions

In this work, the three main contributions are:

1. *An equivalent consumption strategy to reduce fuel consumption for all-electric hybrid marine power system.* A formulation of the cost function based on the Equivalent Consumption Minimization Strategy (ECMS) and a multi-level power management framework is proposed for an all-electric hybrid power system with DC distribution for real-time implementation. The proposed strategy is able to demonstrate fuel savings of up to 24.4% over conventional RB strategy, through real-time experimental validations on an industrial-based hybrid power system.
2. *Enhancement of equivalent consumption strategy to include NO_x emission.* A novel method is proposed to design the equivalent cost with the use of weighting factor, to manage the compromise between consumption and NO_x emission. Proposed method allows the prioritization of control objectives between fuel efficiency and emission reduction, based on operation requirements. Using this method, NO_x emission reduction can be controlled by increasing or decreasing the weighting factor, which is demonstrated through case study over the harbor tugboat operations.
3. *Optimization-based power management for jack-up rigs operations.* The application of the proposed equivalent consumption strategy is further extended to offshore applications, with charge sustaining control. The proposed strategy is able to maintain the battery SOC within the target range, when applied over the draw works process of jack-up rigs operation.

7.3 Recommended future work

In general, the proposed equivalent consumption strategy achieves satisfactory results in improving fuel savings and reducing emissions, as demonstrated for both marine and offshore applications. However, some limitations are observed, which can be addressed in future work.

Firstly, the instantaneous property of the proposed strategy has its pros and cons. The power allocation is determined at the current time step without considering future demands. This exposes a potential risk in a case of battery over-discharging before critical operations, and there is insufficient battery energy available to further assist in the ship operation when required. While the charge sustaining control is one potential solution, another potential method to manage the unexpected fluctuations during practical implementation is the model predictive control. A proof of concept of the model predictive control is investigated and illustrated in Appendix A, which demonstrates comparable fuel consumption as the proposed strategy. For practical implementations, further investigation is required for weighting factors tuning, and determining of input references with improved methods, load prediction, and experimental validation.

Secondly, the engine emission data that is used in this study is not fully representative. More emission trend is required to refine the proposed method. In addition, experimental validation of the proposed method is necessary to validate the NO_x emission saving against real emission data.

Also, further study is required to find an effective algorithm to solve the nonlinear optimization problem presented in the approach to manage NO_x emission, to overcome the constraints highlighted while using the interior point method.

As the performance of the enhanced equivalent consumption strategy for jack-up rigs applications is only verified through numerical simulation, experimental

validation is necessary to demonstrate the practical implementation of the proposed charge sustaining control.

Finally, the development of the optimization-based power management strategies is based on the given system in this study. However, sizing of the power system also plays a part in affecting the optimality of the power management control. Hence, the design of the power system should also be considered as part of the process in power management optimization.

References

- [1] H. O. Kristensen, "Energy demand and exhaust gas emissions of marine engines," *Clean Shipping Currents*, vol. 1, no. 6, pp. 18-26, 2012.
- [2] IMO, "Third IMO Greenhouse Gas Study 2014, Executive Summary and Final Report," *International Maritime Organization, London*, p. 280, 2014.
- [3] EPA, "Integrated Science Assessment for Oxides of Nitrogen and Sulfur Ecological Criteria - Ecological Criteria (Final Report, Dec 2008)," *U.S. Environmental Protection Agency, Washington, DC*, EPA/600/R-08/082F, 2008.
- [4] J.-F. Helfre and P. A. C. Boot, "Emission reduction in the shipping industry: regulations, exposure and solutions," [online]. Available: http://www.sustainalytics.com/sites/default/files/shippingemissions_july2013.pdf, 2013.
- [5] European Environmental Bureau, "Air & Shipping," [online]. Available: http://eeb.org/?page_id=1466&q=Air+%26shipping
- [6] E. Hughes, "A New Chapter for MARPOL Annex VI—Requirements for Technical and Operational Measures to Improve the Energy Efficiency of International Shipping," [online]. Available: <http://www.imo.org/KnowledgeCentre/PapersAndArticlesByIMOSTaff/Documents/A%20new%20chapter%20for%20MARPOL%20Annex%20VI>, 2013.
- [7] R. R. Chan, L. Chua, and T. Tjahjowidodo, "Enabling technologies for sustainable all—Electric hybrid vessels," in *Proc. IEEE International Conference on Sustainable Energy Technologies (ICSET), Hanoi, Vietnam*, pp. 401-406, Nov. 2016.
- [8] A. K. Ådnanes, "Maritime electrical installations and diesel electric propulsion," *ABB AS, Oslo, Norway*, 2003.
- [9] V. M. M. Sáiz and A. P. López, "Future trends in electric propulsion systems for commercial vessels," *Journal of Maritime Research*, vol. 4, no. 2, pp. 81-100, 2007.
- [10] J. Han, J.-F. Charpentier, and T. Tang, "An energy management system of a fuel cell/battery hybrid boat," *Energies*, vol. 7, no. 5, pp. 2799-2820, 2014.
- [11] R. Geertsma, R. Negenborn, K. Visser, and J. Hopman, "Design and control of hybrid power and propulsion systems for smart ships: A review of developments," *Applied Energy*, vol. 194, pp. 30-54, 2017.
- [12] J.-F. Hansen, J. Lindtjoern, T. Myklebust, and K. Vanska, "Onboard DC grid: The newest design for marine power and propulsion systems," *ABB Review*, no. 2, 2012.

-
- [13] L. Kennedy, J. Soong, and J. O. Lindtjorn, "All-electric hybrid propulsion for the next generation of tugboats," in *Proc. Tugology*, London, UK, 2013.
 - [14] F. D. Kanellos, G. J. Tsekouras, and J. Prousalidis, "Onboard DC grid employing smart grid technology: challenges, state of the art and future prospects," *IET Electrical Systems in Transportation*, vol. 5, no. 1, pp. 1-11, 2014.
 - [15] R. Chan, L. Kennedy, and S. Odegaard, "Analysis of fuel efficient all-electric tugboats," in *Proc. Tugology*, London, UK, 2015.
 - [16] J. Hansen, J. Lindtjorn, U. Odegaard, and T. Myklebust, "Increased operational performance of OSVs by Onboard DC Grid," in *Proc. 4th International Conference on Technology and Operation of Offshore Support Vessels*, Singapore, 2011.
 - [17] J. F. Hansen, J. O. Lindtjorn, K. Vanska, and O. Abb, "Onboard DC Grid for enhanced DP operation in ships," in *Proc. Dynamic Positioning Conference*, Houston, 2011.
 - [18] O. C. Nebb, B. Zahedi, J. O. Lindtjorn, and L. Norum, "Increased fuel efficiency in ship LVDC power distribution systems," in *Proc. IEEE Vehicle Power and Propulsion Conference (VPPC)*, 2012, pp. 564-568.
 - [19] Z. Wu, "Comparison of Fuel Consumption on A Hybrid Marine Power Plant with Low-Power versus High-Power Engines," Masters Thesis, Dept. Marine Technol., NTNU, Trondheim, Norway, 2017.
 - [20] M. Kalikatzarakis, R. Geertsma, E. Boonen, K. Visser, and R. Negenborn, "Ship energy management for hybrid propulsion and power supply with shore charging," *Control Engineering Practice*, vol. 76, pp. 133-154, 2018.
 - [21] A. K. Adnanes, "Reduction of fuel consumption and environmental footprint for AHTS and OSVs using electric or hybrid propulsion," presented at the WMTC 2009. [Online]. Available: <http://imare.in/media/30639/paper-no-5a-3-dr-akadnanes.pdf>
 - [22] C. Hodge and D. Mattick, "Electric warship VI," *International maritime technology*, vol. 113, no. 2, pp. 49-63, 2001.
 - [23] C. Hodge and D. Mattick, "The electric warship then, now and later," in *Proc. 9th international naval engineering conference*, 2008, pp. 556-565.
 - [24] G. Sulligoi, A. Vicenzutti, V. Arcidiacono, and Y. Khersonsky, "Voltage stability in large marine-integrated electrical and electronic power systems," *IEEE Transactions on Industry Applications*, vol. 52, no. 4, pp. 3584-3594, 2016.
 - [25] Woodward, "Governing Fundamentals and Power Management," Manual 26260, 2011.
 - [26] J. J. Justo, F. Mwasilu, J. Lee, and J.-W. Jung, "AC-microgrids versus DC-microgrids with distributed energy resources: A review," *Renewable and Sustainable Energy Reviews*, vol. 24, pp. 387-405, 2013.

-
- [27] J. F. Hansen, "Modelling and control of marine power systems," Ph.D. Thesis, Dept. Marine Technol., NTNU, Trondheim, Norway, 2000.
 - [28] T. A. Myklebust and A. K. Ådnanes, "Parallel hybrid propulsion for AHTS," *ABB Generations*, 2012.
 - [29] A. A. Alexander, "Modeling power distribution system of an electric ship for design and control," Ph.D. Thesis, School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore, 2015.
 - [30] N. Karim, R. Lisner, H. Kazemi, and F. Annaz, "Rule-based power management for the all-electric ship," in *Proc. Australian University power engineering conference*, 2002.
 - [31] B. Zahedi and L. E. Norum, "Voltage regulation and power sharing control in ship LVDC power distribution systems," in *Proc. 2013 15th European Conference on Power Electronics and Applications (EPE)*, 2013, pp. 1-8.
 - [32] J. O. Lindtjørn, F. Wendt, B. Gundersen, and J. Hansen, "Demonstrating the benefits of advanced power systems and energy storage for DP vessels," in *Proc. Dyn. Positioning Conf.*, 2014, pp. 1-23.
 - [33] M. R. Miyazaki, A. J. Sørensen, and B. J. Vartdal, "Reduction of fuel consumption on hybrid marine power plants by strategic loading with energy storage devices," *IEEE Power and Energy Technology Systems Journal*, vol. 3, no. 4, pp. 207-217, 2016.
 - [34] S. G. Wirasingha and A. Emadi, "Classification and review of control strategies for plug-in hybrid electric vehicles," *IEEE Transactions on vehicular technology*, vol. 60, no. 1, pp. 111-122, 2011.
 - [35] F. R. Salmasi, "Control strategies for hybrid electric vehicles: Evolution, classification, comparison, and future trends," *IEEE Transactions on vehicular technology*, vol. 56, no. 5, pp. 2393-2404, 2007.
 - [36] A. Panday and H. O. Bansal, "A review of optimal energy management strategies for hybrid electric vehicle," *International Journal of Vehicular Technology*, vol. 2014, 2014.
 - [37] M. A. Karbaschian and D. Söffker, "Review and comparison of power management approaches for hybrid vehicles with focus on hydraulic drives," *Energies*, vol. 7, no. 6, pp. 3512-3536, 2014.
 - [38] A. Brahma, Y. Guezennec, and G. Rizzoni, "Optimal energy management in series hybrid electric vehicles," in *Proc. American Control Conference*, 2000, vol. 1, no. 6, pp. 60-64.
 - [39] J. Knapp, A. Chapman, S. Mody, and T. Steffen, "Optimal control inputs for fuel economy and emissions of a series hybrid electric vehicle," Presented at: SAE 2015 World Congress and Exhibition: Leading Mobility Innovation, 21st-23rd April 2015, Detroit, USA.
 - [40] L. V. Pérez, G. R. Bossio, D. Moitre, and G. O. García, "Optimization of power management in an hybrid electric vehicle using dynamic

-
- programming," *Mathematics and Computers in Simulation*, vol. 73, no. 1-4, pp. 244-254, 2006.
- [41] R. Wang and S. M. Lukic, "Dynamic programming technique in hybrid electric vehicle optimization," in *Proc. IEEE International Electric Vehicle Conference (IEVC)*, 2012, 2012, pp. 1-8
 - [42] C. Weng, Y. Wang, V. Tsourapas, C. Patil, and J. Sun, "Optimal control of hybrid electric vehicles with power split and torque split strategies: A comparative case study," in *American Control Conference (ACC)*, 2011, pp. 2131-2136
 - [43] Y. Zou, H. Shi-jie, L. Dong-ge, G. Wei, and X.-s. Hu, "Optimal energy control strategy design for a hybrid electric vehicle," *Discrete Dynamics in Nature and Society*, vol. 2013, Article ID 132064, 8 pages, 2013. <https://doi.org/10.1155/2013/132064>.
 - [44] L. Lai and M. Ehsani, "Dynamic programming optimized constrained engine on and off control strategy for parallel HEV," in *Proc. 2013 IEEE Vehicle Power and Propulsion Conference (VPPC)*, 2013, pp. 1-5
 - [45] C.-C. Lin, J.-M. Kang, J. Grizzle, and H. Peng, "Energy management strategy for a parallel hybrid electric truck," in *Proc. American Control Conference*, 2001, vol. 4, pp. 2878-2883
 - [46] C.-C. Lin, H. Peng, J. W. Grizzle, and J.-M. Kang, "Power management strategy for a parallel hybrid electric truck," *IEEE transactions on control systems technology*, vol. 11, no. 6, pp. 839-849, 2003.
 - [47] J. Liu and H. Peng, "Modeling and control of a power-split hybrid vehicle," *IEEE transactions on control systems technology*, vol. 16, no. 6, pp. 1242-1251, 2008.
 - [48] C.-C. Lin, H. Peng, and J. Grizzle, "A stochastic control strategy for hybrid electric vehicles," in *Proc. American Control Conference*, 2004, vol. 5, pp. 4710-4715: IEEE.
 - [49] T. Leroy, J. Malaizé, and G. Corde, "Towards real-time optimal energy management of HEV powertrains using stochastic dynamic programming," in *Proc. IEEE Vehicle Power and Propulsion Conference (VPPC)*, 2012, pp. 383-388
 - [50] G. Paganelli, S. Delprat, T.-M. Guerra, J. Rimaux, and J.-J. Santin, "Equivalent consumption minimization strategy for parallel hybrid powertrains," in *Proc. IEEE 55th Vehicular Technology Conference, VTC Spring*, 2002, vol. 4, pp. 2076-2081
 - [51] O. Grondin, L. Thibault, and C. Quérel, "Energy management strategies for diesel hybrid electric vehicle," *Oil & Gas Science and Technology—Revue d'IFP Energies nouvelles*, vol. 70, no. 1, pp. 125-141, 2015.
 - [52] G. Paganelli, M. Tateno, A. Brahma, G. Rizzoni, and Y. Guezennec, "Control development for a hybrid-electric sport-utility vehicle: strategy,

- implementation and field test results," in *Proc. American Control Conference*, 2001, vol. 6, pp. 5064-5069: IEEE.
- [53] H. Sagha, S. Farhangi, and B. Asaei, "Modeling and design of a NO_x emission reduction strategy for lightweight hybrid electric vehicles," in *Proc. 35th Annual Conference of IEEE Industrial Electronics (IECON'09)*, 2009, pp. 334-339
- [54] M. Khodabakhshian, L. Feng, and J. Wikander, "Improving fuel economy and robustness of an improved ECMS method," in *Proc. 10th IEEE International Conference on Control and Automation (ICCA)*, 2013, pp. 598-603
- [55] J. McDonald and S. Fallah, "A Novel Equivalent Consumption Minimisation Strategy for a Series Hybrid Electric Vehicle," *J Robot Mech Eng Resr*, vol. 1, no. 1, pp. 24-30, 2015.
- [56] J. Couch, L. Fiorentini, and M. Canova, "An ECMS-Based Approach for the Energy Management of a Vehicle Electrical System," *IFAC Proceedings Volumes*, vol. 46, no. 21, pp. 115-120, 2013.
- [57] L. Johannessson, S. Pettersson, and B. Egardt, "Predictive energy management of a 4QT series-parallel hybrid electric bus," *Control Engineering Practice*, vol. 17, no. 12, pp. 1440-1453, 2009.
- [58] F. Payri, C. Guardiola, B. Pla, and D. Blanco-Rodriguez, "On a stochastic approach of the ecms method for energy management in hybrid electric vehicles," *IFAC Proceedings Volumes*, vol. 45, no. 30, pp. 341-348, 2012.
- [59] L. Serrao, S. Onori, and G. Rizzoni, "A comparative analysis of energy management strategies for hybrid electric vehicles," *Journal of Dynamic Systems, Measurement, and Control*, vol. 133, no. 3, p. 031012, 2011.
- [60] T. Hofman, M. Steinbuch, R. Van Druten, and A. Serrarens, "Rule-based energy management strategies for hybrid vehicles," *International Journal of Electric and Hybrid Vehicles*, vol. 1, no. 1, pp. 71-94, 2007.
- [61] D. Zhao, R. Stobart, G. Dong, and E. Winward, "Real-time energy management for diesel heavy duty hybrid electric vehicles," *IEEE Transactions on Control Systems Technology*, vol. 23, no. 3, pp. 829-841, 2015.
- [62] J. Han, Y. Park, and Y.-s. Park, "A novel updating method of equivalent factor in ECMS for prolonging the lifetime of battery in fuel cell hybrid electric vehicle," *IFAC Proceedings Volumes*, vol. 45, no. 30, pp. 227-232, 2012.
- [63] C. Musardo, G. Rizzoni, Y. Guezennec, and B. Staccia, "A-ECMS: An adaptive algorithm for hybrid electric vehicle energy management," *European Journal of Control*, vol. 11, no. 4-5, pp. 509-524, 2005.
- [64] S. Kutter and B. Bäker, "An iterative algorithm for the global optimal predictive control of hybrid electric vehicles," in *Proc. IEEE Vehicle Power and Propulsion Conference (VPPC)*, 2011, pp. 1-6

-
- [65] L. Qiu, L. Qian, H. Zomorodi, and P. Pisu, "Design and optimization of equivalent consumption minimization strategy for 4WD hybrid electric vehicles incorporating vehicle connectivity," *Science China Technological Sciences*, vol. 61, no. 1, pp. 147-157, 2018.
 - [66] A. Sciarretta, M. Back, and L. Guzzella, "Optimal control of parallel hybrid electric vehicles," *IEEE Transactions on control systems technology*, vol. 12, no. 3, pp. 352-363, 2004.
 - [67] N. Kim, S. Cha, and H. Peng, "Optimal control of hybrid electric vehicles based on Pontryagin's minimum principle," *IEEE Transactions on Control Systems Technology*, vol. 19, no. 5, pp. 1279-1287, 2011.
 - [68] I. E. Aiteur, C. Vlad, and E. Godoy, "Optimization-based energy management strategies for electric vehicles," in *Proc. 41st Annual Conference of the IEEE Industrial Electronics Society (IECON)*, 2015, pp. 003449-003454.
 - [69] H. Li, A. Ravey, A. N'Diaye, and A. Djerdir, "Equivalent consumption minimization strategy for hybrid electric vehicle powered by fuel cell, battery and supercapacitor," in *Proc. 42nd Annual Conference of the IEEE Industrial Electronics Society (IECON)* 2016, pp. 4401-4406.
 - [70] P. Rodatz, G. Paganelli, A. Sciarretta, and L. Guzzella, "Optimal power management of an experimental fuel cell/supercapacitor-powered hybrid vehicle," *Control engineering practice*, vol. 13, no. 1, pp. 41-53, 2005.
 - [71] P. García, J. P. Torreglosa, L. M. Fernández, and F. Jurado, "Viability study of a FC-battery-SC tramway controlled by equivalent consumption minimization strategy," *International journal of hydrogen energy*, vol. 37, no. 11, pp. 9368-9382, 2012.
 - [72] S. N. Motapon, L.-A. Dessaint, and K. Al-Haddad, "A comparative study of energy management schemes for a fuel-cell hybrid emergency power system of more-electric aircraft," *IEEE transactions on industrial electronics*, vol. 61, no. 3, pp. 1320-1334, 2014.
 - [73] C. Bordons, M. A. Ridao, A. Pérez, A. Arce, and D. Marcos, "Model predictive control for power management in hybrid fuel cell vehicles," in *Proc. IEEE Vehicle Power and Propulsion Conference (VPPC)*, 2010, pp. 1-6: IEEE.
 - [74] H. A. Borhan, A. Vahidi, A. M. Phillips, M. L. Kuang, and I. V. Kolmanovsky, "Predictive energy management of a power-split hybrid electric vehicle," in *Proc. American Control Conference*, 2009, pp. 3970-3976: IEEE.
 - [75] H. Borhan, A. Vahidi, A. M. Phillips, M. L. Kuang, I. V. Kolmanovsky, and S. Di Cairano, "MPC-based energy management of a power-split hybrid electric vehicle," *IEEE Transactions on Control Systems Technology*, vol. 20, no. 3, pp. 593-603, 2012.

-
- [76] H. A. Borhan, C. Zhang, A. Vahidi, A. M. Phillips, M. L. Kuang, and S. Di Cairano, "Nonlinear model predictive control for power-split hybrid electric vehicles," in *Proc. 49th IEEE Conference on Decision and Control (CDC)*, 2010, pp. 4890-4895.
 - [77] H. Borhan, "Optimization-based power management of hybrid power systems with applications in advanced hybrid electric vehicles and wind farms with battery storage," Ph.D. Thesis, Dept. Mech. Engr. Clemson University, Clemson, South Carolina, 2011.
 - [78] G. Ripaccioli, D. Bernardini, S. Di Cairano, A. Bemporad, and I. Kolmanovsky, "A stochastic model predictive control approach for series hybrid electric vehicle power management," in *Proc. American Control Conference (ACC)*, 2010, pp. 5844-5849.
 - [79] S. Di Cairano, D. Bernardini, A. Bemporad, and I. V. Kolmanovsky, "Stochastic MPC with learning for driver-predictive vehicle control and its application to HEV energy management," *IEEE Trans. Contr. Sys. Techn.*, vol. 22, no. 3, pp. 1018-1031, 2014.
 - [80] C. Sun, X. Hu, S. J. Moura, and F. Sun, "Velocity Predictors for Predictive Energy Management in Hybrid Electric Vehicles," *IEEE Trans. Contr. Sys. Techn.*, vol. 23, no. 3, pp. 1197-1204, 2015.
 - [81] T.-V. Vu, C.-K. Chen, and C.-W. Hung, "A model predictive control approach for fuel economy improvement of a series hydraulic hybrid vehicle," *Energies*, vol. 7, no. 11, pp. 7017-7040, 2014.
 - [82] G. Seenumani, J. Sun, and H. Peng, "A Numerically Efficient Iterative procedure for hybrid power system optimization using sensitivity functions," in *American Control Conference, 2007. ACC'07*, 2007, pp. 4738-4743: IEEE.
 - [83] G. Seenumani, J. Sun, and H. Peng, "Real-time power management of integrated power systems in all electric ships leveraging multi time scale property," *IEEE Transactions on Control Systems Technology*, vol. 20, no. 1, pp. 232-240, 2012.
 - [84] G. Seenumani, "Real-time Power Management of Hybrid Power Systems in All Electric Ship Applications," Ph.D. Thesis, Dept. Mech. Engr., University of Michigan, 2010.
 - [85] G. Seenumani, J. Sun, and H. Peng, "A hierarchical optimal control strategy for power management of hybrid power systems in all electric ships applications," in *Proc. 49th IEEE Conference on Decision and Control (CDC)*, 2010, pp. 3972-3977.
 - [86] G. Seenumani, H. Peng, and J. Sun, "A reference governor-based hierarchical control for failure mode power management of hybrid power systems for all-electric ships," *Journal of power sources*, vol. 196, no. 3, pp. 1599-1607, 2011.

-
- [87] P. Stone *et al.*, "Shipboard power management using constrained nonlinear model predictive control," in *Proc. IEEE Electric Ship Technologies Symposium (ESTS)*, 2015, pp. 1-7.
 - [88] H. Park, "Real-time Predictive Control of Constrained Nonlinear Systems Using the IPA-SQP Approach," Ph.D. Thesis, Dept. Mech. Engr., University of Michigan, 2014.
 - [89] H. Park *et al.*, "Real-time model predictive control for shipboard power management using the IPA-SQP approach," *IEEE Transactions on Control Systems Technology*, vol. 23, no. 6, pp. 2129-2143, 2015.
 - [90] T. Van Vu, D. Gonsoulin, F. Diaz, C. S. Edrington, and T. El-Mezyani, "Predictive control for energy management in ship power systems under high-power ramp rate loads," *IEEE Transactions on Energy Conversion*, vol. 32, no. 2, pp. 788-797, 2017.
 - [91] J. Hou, J. Sun, and H. Hofmann, "Mitigating power fluctuations in electrical ship propulsion using model predictive control with hybrid energy storage system," in *American Control Conference (ACC)*, 2014, pp. 4366-4371: IEEE.
 - [92] J. Hou, J. Sun, and H. F. Hofmann, "Mitigating power fluctuations in electric ship propulsion with hybrid energy storage system: Design and analysis," *IEEE Journal of Oceanic Engineering*, 2017.
 - [93] J. Hou, "Control and Optimization of Electric Ship Propulsion Systems with Hybrid Energy Storage," Ph.D. Thesis, Dept. Mech. Engr., University of Michigan, 2017.
 - [94] A. Haseltalab, R. R. Negenborn, and G. Lodewijks, "Multi-level predictive control for energy management of hybrid ships in the presence of uncertainty and environmental disturbances," *IFAC-PapersOnLine*, vol. 49, no. 3, pp. 90-95, 2016.
 - [95] T. I. Bø and T. A. Johansen, "Battery power smoothing control in a marine electric power plant using nonlinear model predictive control," *IEEE Transactions on Control Systems Technology*, vol. 25, no. 4, pp. 1449-1456, 2017.
 - [96] A. Haseltalab and R. R. Negenborn, "Predictive on-board power management for all-electric ships with DC distribution architecture," in *Proc. OCEANS 2017*, Aberdeen, 2017, pp. 1-8.
 - [97] T. Vu, J. Dhupia, A. Ayu, L. Kennedy, and A. Adnanes, "Control Optimization for Power Distribution System of Electric Tugboats: Deterministic Load Demand," in *Proc. International Symposium on Flexible Automation, Awaji-Island, Hyogo, Japan*, 2014, pp. 14-16.
 - [98] T. L. Vu, A. A. Ayu, J. S. Dhupia, L. Kennedy, and A. K. Adnanes, "Power management for electric tugboats through operating load estimation," *IEEE Transactions on Control Systems Technology*, vol. 23, no. 6, pp. 2375-2382, 2015.

-
- [99] T. L. Vu, J. S. Dhupia, A. A. Ayu, L. Kennedy, and A. K. Adnanes, "Optimal power management for electric tugboats with unknown load demand," in *American Control Conference (ACC)*, 2014, 2014, pp. 1578-1583: IEEE.
 - [100] E. K. Dedes, "Investigation of hybrid systems for diesel powered ships," Ph.D. Thesis, Faculty of Engineering and the Environment, University of Southampton, 2013.
 - [101] E. K. Dedes, D. A. Hudson, and S. R. Turnock, "Investigation of Diesel Hybrid systems for fuel oil reduction in slow speed ocean going ships," *Energy*, vol. 114, pp. 444-456, 2016.
 - [102] H. Grimmelius, P. de Vos, M. Krijgsman, and E. van Deursen, "Control of hybrid ship drive systems," in *10th international conference on computer and IT applications in the maritime industries. Berlin: Technische Universitat Hamburg-Harburg*, 2011, pp. 1-14.
 - [103] A. M. Bassam, A. B. Phillips, S. R. Turnock, and P. A. Wilson, "Development of a multi-scheme energy management strategy for a hybrid fuel cell driven passenger ship," *International Journal of Hydrogen Energy*, vol. 42, no. 1, pp. 623-635, 2017.
 - [104] F. D. Kanellos, J. M. Prousalidis, and G. J. Tsekouras, "Control system for fuel consumption minimization–gas emission limitation of full electric propulsion ship power systems," in *Proc. Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, vol. 228, no. 1, pp. 17-28, 2014.
 - [105] F. D. Kanellos, G. J. Tsekouras, and N. D. Hatziaargyriou, "Optimal demand-side management and power generation scheduling in an all-electric ship," *IEEE Transactions on Sustainable Energy*, vol. 5, no. 4, pp. 1166-1175, 2014.
 - [106] F. Kanellos, "Optimal power management with GHG emissions limitation in all-electric ship power systems comprising energy storage systems," *IEEE Transactions on Power Systems*, vol. 29, no. 1, pp. 330-339, 2014.
 - [107] F. D. Kanellos, A. Anvari-Moghaddam, and J. M. Guerrero, "A cost-effective and emission-aware power management system for ships with integrated full electric propulsion," *Electric Power Systems Research*, vol. 150, pp. 63-75, 2017.
 - [108] G. Papalambrou, S. Samokhin, S. Topaloglou, N. Planakis, N. Kyrtatos, and K. Zenger, "Model Predictive Control for Hybrid Diesel-Electric Marine Propulsion," *IFAC-PapersOnLine*, vol. 50, no. 1, pp. 11064-11069, 2017.
 - [109] J. Zhang, "Modeling and dynamics analysis of electro-mechanical power-trains," Ph.D. Thesis, School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore, 2014.
 - [110] dSPACE, "Controller Board—Hardware Installation and Configuration," *Germany: dSPACE GmbH, Release*, vol. 6, 2007.

-
- [111] T. H. Syverud, "Modeling and Control of a DC-grid Hybrid Power System with Battery and Variable Speed Diesel Generators," Masters Thesis, Dept. Elec. Pwr. Engr., NTNU, Trondheim, Norway, 2016.
 - [112] B. Zahedi and L. E. Norum, "Modeling and simulation of all-electric ships with low-voltage DC hybrid power systems," *IEEE Transactions on Power Electronics*, vol. 28, no. 10, pp. 4525-4537, 2013.
 - [113] P. Dandeno *et al.*, "IEEE guide for synchronous generator modeling practices and applications in power system stability analyses," *IEEE Std. 1110-2002*, pp. 1-72, 2003.
 - [114] O. Tremblay and L.-A. Dessaint, "Experimental validation of a battery dynamic model for EV applications," *World Electric Vehicle Journal*, vol. 3, no. 2, pp. 289-298, 2009.
 - [115] W.-Y. Chang, "The state of charge estimating methods for battery: A review," *ISRN Applied Mathematics*, vol. 2013, 2013.
 - [116] L. W. Yao, J. Aziz, P. Y. Kong, and N. Idris, "Modeling of lithium-ion battery using MATLAB/simulink," in *Proc. 39th Annual Conference of the IEEE Industrial Electronics Society (IECON)*, 2013, pp. 1729-1734.
 - [117] C. Wang, R. Xiong, H. He, X. Ding, and W. Shen, "Efficiency analysis of a bidirectional DC/DC converter in a hybrid energy storage system for plug-in hybrid electric vehicles," *Applied energy*, vol. 183, pp. 612-622, 2016.
 - [118] B. Zahedi and L. E. Norum, "Modelling and simulation of hybrid electric ships with DC distribution systems," in *Proc. 15th European Conference on Power Electronics and Applications (EPE)*, 2013, pp. 1-10.
 - [119] I. Aharon, A. Kuperman, and D. Shmilovitz, "Analysis of bi-directional buck-boost converter for energy storage applications," in *Proc. 39th Annual Conference of the IEEE Industrial Electronics Society (IECON)* 2013, pp. 858-863.
 - [120] B. Hauke, "Basic calculation of a boost converter's power stage," *Texas Instruments, Application Report November*, pp. 1-9, 2009.
 - [121] H. Brigitte, "Basic calculation of a buck converter's power stage," *Texas Instruments, Dallas, Texas, Tech. Rep. SLVA477*, 2011.
 - [122] B. Zahedi, L. E. Norum, and K. B. Ludvigsen, "Optimization of fuel consumption in shipboard power systems," in *Proc. 39th Annual Conference of the IEEE Industrial Electronics Society (IECON)* 2013, pp. 1124-1129: IEEE.
 - [123] M. Drilling, "Maersk Giant," 2014.
 - [124] S. O. S. Espen Haugan, "Energy Storage for Reducing Energy Losses in Drilling Platforms," Siemens 2012.
 - [125] A. R. Bratfos, "DC Grid with Energy Storage for Jack-up rigs," Master's Thesis, Dept. Elec. Pwr. Engr., NTNU, Trondheim, Norway, 2014.
 - [126] S. Onori, L. Serrao, and G. Rizzoni, *Hybrid electric vehicles: Energy management strategies*. Springer, 2016.

Publications

1. **Chua, L.W.Y.**, Chan, R., Tjahjowidodo, T., and Seet, G.L., “Optimizing Fuel Efficiency and Emission Reduction Through Intelligent Power Management for All-Electric Hybrid Vessels” *submitted to ABB Generations*, 2019
2. **Chua, L.W.Y.**, Tjahjowidodo, T., Seet, G.L., and Chan, R. (2018). “Implementation of Optimization-Based Power Management for All-Electric Hybrid Vessels” *IEEE Access*, 6, 74339-74354, DOI: 10.1109/ACCESS.2018.2883324.
3. **Chua, L.W.Y.**, Tjahjowidodo, T., Seet, G.L. and Chan, R. (2017). “Optimizing Fuel Savings and Power System Reliability for All-Electric Hybrid Vessels using Model Predictive Control”, *Proceedings of 2017 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, Munich, Germany, pp. 1532-1537.
4. Chan, R., **Chua, L.W.Y.**, and Tjahjowidodo, T. (2016). “Enabling Technologies for Sustainable All-Electric Hybrid Vessels” (invited paper), *Proceedings of IEEE International Conference on Sustainable Energy Technologies (ICSET)*, Hanoi, Vietnam, pp. 401-406.
5. **Chua, L.W.Y.**, Tjahjowidodo, T., Seet, G.L., Chan, R., and Ådnanes, A.K. (2016). “Equivalent Consumption Minimization Strategy for Hybrid All-Electric Tugboats to Optimize Fuel Savings”, *Proceedings of 2016 American Control Conference*, Boston, MA, pp. 6803-6808.

Appendix A

Model Predictive Control Approach for All-Electric Hybrid Vessel²

Preliminary studies on adopting a model predictive control approach is investigated for the case of a harbor tugboat operations for proof of concept. Numerical illustrations of the formulated approach is demonstrated through simulation. Simulation results show close performance with proposed ECMS, demonstrating substantial fuel savings compared to RB approach.

A.1 Concept

The model predictive control (MPC) is widely utilized by different industries and applications, including HEVs and naval vessel applications as described earlier in the literature studies. In this work, a preliminary study is conducted to explore MPC approach for an all-electric hybrid vessel. The main objective of this preliminary study is a proof of concept of the MPC approach, which sets as a foundation for further development of optimal power management control strategies with this approach. The MPC approach is targeted as a supervisory control that can be implemented to existing power management systems in the same way as the

² The main findings of this work are presented in:

- Chua, L.W.Y., Tjahjowidodo, T., Seet, G.G.L. and Chan, R. (2017). "Optimizing Fuel Savings and Power System Reliability for All-Electric Hybrid Vessels using Model Predictive Control", *Proceedings of 2017 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, Munich, Germany, pp. 1532-1537.

proposed ECMS at the supervisory level of the multi-level power management framework. The main control objective will focus on fuel reduction.

MPC utilizes current state information to predict the plant output within the prediction horizon, based on the defined plant model in the controller. At every time step, MPC solves the optimization problem over the prediction horizon to generate the control sequence. The number of elements in the control sequence is determined by the defined control horizon. Receding horizon control is applied where the first element of the control sequence is implemented. The prediction window then moves to the next time step and the process repeats.

A.2 Problem formulation

A simplified control-oriented plant model of the all-electric hybrid power system is proposed for the prediction model of the MPC controller. A few assumptions were taken for the controller design:

1. The power management problem considers the fuel consumption at steady-state values, fuel consumption during engine ramping is not considered.
2. The dynamics of the power converters are in the order of milliseconds and therefore it is assumed to be negligible. Losses through the power converters are assumed to be constant.
3. Transmission losses of genset, drivetrain and battery efficiencies are assumed constant. The temperature and aging effects of batteries are not considered.

For the genset, the first order model is used to reflect the transient response of the genset, expressed as:

$$P_{gen,i} = n_{gen,i} \cdot \frac{1}{\tau_{gen,i}s + 1} \cdot P_{eng,i} \quad (A.1)$$

where $\tau_{gen,i}$ is the time constant of the genset which reflects the response time of the genset. $P_{eng,i}$ is the power reference of i th genset. $P_{gen,i}$ (W) and $n_{gen,i}$ are the genset power output and genset efficient, similar to previous definitions.

For the batteries, the SOC is determined with the coulomb counting method as before:

$$\dot{SOC} = \frac{P_{batt}}{Q_n \cdot V_{oc} \cdot 3600} \quad (A.2)$$

where $\dot{SOC}$ is the change in SOC in each time step, V_{oc} (V) is the open circuit voltage of the battery, Q_n (Ah) is the nominal battery capacity. P_{batt} (W) is the battery power output where $P_{batt} \geq 0$ indicates battery discharging and $P_{batt} < 0$ indicates battery charging.

The transmission losses between the power sources and load demand is assumed to be:

$$P_{load} = n_{dt} \cdot \frac{1}{\tau_{dt}S + 1} \cdot P_{total} \quad (A.3)$$

$$P_{total} = \sum_{i=1}^{N_{gen}} P_{gen,i} + n_{batt} \cdot P_{batt} \quad (A.4)$$

where P_{load} (W) is the total load demand and P_{total} (W) is the total supplied power from the power sources. n_{dt} and n_{batt} are the efficiencies of the drive-train and batteries respectively. N_{gen} is the total number of gensets and τ_{dt} is the drive-train time constant.

The prediction model is constructed in discrete time by discretizing Eq. (A.1)-(A.4) using Euler's Approximation. Using the same set of system design used in this study with 2 gensets and batteries as the main power sources, the state-space representation of the prediction model is formulated as:

$$x(k+1) = A(x) + Bu(k)$$

$$y(k) = Cx(k)$$

$$x = \begin{bmatrix} P_{gen,1} \\ P_{gen,2} \\ SOC \\ P_{load} \end{bmatrix}, u = \begin{bmatrix} P_{eng,1} \\ P_{eng,2} \\ P_{batt} \end{bmatrix}, y = x \quad (A.5)$$

where x is the state variables, u is the control variables and y is the output variable. The power output from the generators, SOC of the battery and total load demand are defined as the state variables, and the power reference of the genset and batteries are defined as the control variables. A , B and C are state matrices defined based on the discretized plant model. This formulation is not restricted to two gensets, the state-space matrix can be expanded accordingly to include more power sources. At every time step, this prediction model is used to determine the control input over the control horizon and estimate the plant output.

The power management problem is then formulated with standard MPC cost function formulation:

$$\begin{aligned} \min L = & \sum_{j=1}^{N_p} \left\{ \alpha_1 [P_{gen,1}^*(k+j) - P_{gen,1}(k+j)]^2 \right. \\ & + \alpha_2 [P_{gen,2}^*(k+j) - P_{gen,2}(k+j)]^2 \\ & + \alpha_3 [SOC^*(k+j) - SOC(k+j)]^2 \\ & + \alpha_4 [P_{act_load}^*(k+j) - P_{load}(k+j)]^2 \Big\} \\ & + \sum_{j=1}^{N_c} \left\{ \beta_1 [\Delta P_{eng,1}]^2 + \beta_2 [\Delta P_{eng,2}]^2 + \beta_3 [\Delta P_{batt}]^2 \right\} \end{aligned} \quad (A.6)$$

Subjected to linear inequality constraints:

$$P_{gen,i_min} \leq P_{gen,i} \leq P_{gen,i_max} \quad (A.7)$$

$$-P_{batt_min} \leq P_{batt} \leq P_{batt_max} \quad (A.8)$$

$$SOC_{min} \leq SOC \leq SOC_{max} \quad (A.9)$$

where N_p and N_c are the prediction and control horizon, $\alpha_1, \alpha_2, \alpha_3, \alpha_4$ are the weighting factors to penalize the control reference tracking error, and $\beta_1, \beta_2, \beta_3$ are the weighting factors to penalize the control action within the control horizon to avoid sudden and abrupt changes. $P_{gen,1}^*(W)$, $P_{gen,2}^*(W)$, SOC^* , $P_{act_load}^*(W)$ are the power input references of the gensets, SOC reference and actual load demand respectively.

A.3 Proof of concept: Numerical illustrations

The main control objective is to minimize fuel consumption while ensuring the system reliability. To achieve fuel efficiency, it is ideal to operate the gensets around the optimal loading range as shown in earlier chapters. Therefore, $P_{gen,1}^*$ and $P_{gen,2}^*$ are set to the engine load at the lowest SFOC value. From the engine data shown in Fig 4.2, the fuel-efficient point is about 75% of engine load, and hence the power input reference of the gensets are set as follows:

$$P_{gen,1}^* = 0.75 \cdot P_{gen,1_max} \quad (A.10)$$

$$P_{gen,2}^* = 0.75 \cdot P_{gen,2_max} \quad (A.11)$$

To ensure system reliability, firstly, the power demand tracking $[P_{act_load}^*(k+j) - P_{load}(k+j)]$ is included in the cost function formulation to minimize the tracking error, ensuring that power demanded by the load are met. Secondly, in previous study on ECMS approach, a potential problem is identified where over-discharging of the

battery before the peak load demand may compromise on the system's reliability. Therefore, SOC^* is set to a mid-range value between the upper and lower SOC limits. In this way, power battery is penalized when SOC deviates from the set point, indirectly enforcing charge sustaining control. This aims to prevent the battery to fully discharge to the lower SOC limit before critical operations with peak load demands.

The weighting factors are also key factors that must be carefully tuned to achieve the desired control objectives. The allocated weighting factors are shown in Table A.1. The tuning of the weighting factors for MPC controller design is an intuitive process. Firstly, a heavy weighting is allocated for load demand tracking to ensure the stability of the power system. Secondly, the weighting factor related to tracking of SOC reference is first multiplied by a factor of 10^6 , so that the SOC value expressed in percentage is comparative to other power elements which are expressed in values more than 10^6W . In addition, to maintain genset 1 near the optimal operating point and to be utilized before the genset 2 is required to switch on, weighting factor for genset 1 tracking is penalized more than genset 2. The same weighting factors are allocated to both genset to penalize the control action to mitigate abrupt changes. A lower weighting factor is allocated to the battery power in comparison, since battery with faster response time can handle power fluctuations better.

Table A.1 Weighting factors

α_1	α_2	α_3	α_4	β_1	β_2	β_3
0.5	0.01	6×10^6	20	2	2	0.1

At each sampling time, MPC is converted to a Quadratic Programming (QP) problem. The optimization problem is solved to generate the optimal values of the control variables within the constraints. MPC is implemented with the MPC toolbox of

MATLAB/Simulink, with a sample time (T_s) of 1s, prediction horizon (N_p) of 60, and control horizon (N_c) of 10. The performance of the proposed MPC is evaluated through the harbour tug load case study shown in Fig. 4.4. The same set of system parameters are used, as shown in Table A.1. The cost function is solved and the numerical results over the harbour tug operation cycle are shown in Fig. A.1.

Figure A.1 Numerical results of MPC over harbor tug operation

From the results shown, it is observed that genset 1 is operating with engine loading below 50% for a significant portion of time, which is not optimal for fuel consumption, engine performance and combustion process. Whereas, genset 2 is online only during the ship assist operation. This is mainly due to the tuning of the weighting factors where genset 1 is penalized more when it deviates from the set

point. This forces genset 1 to go online to meet the set point. Furthermore, since genset 1 is online throughout the operation, it also results in less utilization of the battery. The SOC of the battery stays above the set point for majority of the operation cycle. To achieve better performance in terms of fuel efficiency, improvements are made to refine the input references and weighting factors are further adjusted.

A.4 Refined input references

Here, the reference inputs are refined. The aim is to operate the gensets during the transit and ship assist operation, and to utilize batteries during standby for the hotel and service loads, which is assumed to be between 50 kW to 60 kW. Hence, the input references for genset 1 and 2 are defined as follows:

$$P_{gen,1}^* = \begin{cases} 0 & \text{if } 0 \leq P_{act_load} < 60000 \\ 0.75 \cdot P_{gen,1_max} & \text{if } P_{act_load} \geq 60000 \end{cases} \quad (7.12)$$

$$P_{gen,2}^* = \begin{cases} 0 & \text{if } 0 \leq P_{act_load} < 60000 \\ 0.75 \cdot P_{gen,2_max} & \text{if } P_{act_load} \geq 60000 \end{cases} \quad (7.13)$$

A change in the input references requires further tuning of the weighting factors. The new set of weighting allocations is shown in Table A.2.

Table A.1 Weighting factors for refined input references

α_1	α_2	α_3	α_4	β_1	β_2	β_3
1	0.01	6×10^6	20	0.1	3	0.01

The numerical results are shown in Fig A.2. Therein, it is observed that genset 1 is operated at a much higher loading that is close to the optimal operating point of the

engine. The battery is utilized more optimally to supply for the service and hotel loads during standby periods to avoid low engine loadings. Also, it is interesting to note that genset 2 continues to operate at relatively high engine loading for a short duration into the standby period after ship assist operation. This is likely due to the weighting allocation that penalizes more on the deviation of the SOC from the set point. As the SOC has depleted below the set point at this point of time, genset 2 continues to operate near the optimal operating point to meet the load demand and channels excess power to charge the battery simultaneously, to recover the battery SOC back to the set point.

Figure A.2 Numerical results of MPC over harbor tug operation with refined input references

A.5 Performance comparison with ECMS approach

To assess the performance of the MPC approach in achieving fuel reduction, the results with refined input reference is compared with the numerical results of the proposed ECMS approach, as shown in Fig A.3.

From the figure, it is observed that the engine loading is well maintained near optimal operating point under both strategies. In the case of the proposed MPC, genset 1 loading varies from 60%-90% during the first half of the operation cycle, while utilizing battery energy at the same time to meet the load demand since battery SOC is above the SOC input reference set point. While for ECMS strategy, genset loading is consistent at about 90%, and the battery usage is minimal. With MPC strategy, genset 2 extends its operation into the standby period after ship assist operation to meet load demands and channel excess energy into the battery. In some cases, this is desirable to maintain the battery capacity for direct transits to another work location thereafter without the need to returning to the port. The trade-off will be greater amount of fuel consumed. While with ECMS strategy, power source is switched from genset 2 to the battery when ship enters the standby period after ship assist operations.

Under the proposed MPC, battery is utilized more when SOC is above the SOC reference set point, while battery usage is penalised when SOC falls below the reference set point. This ensures that battery does not fully discharge before the ship assist operation. In addition, by ensuring that SOC is above the minimum limit, it provides some allowances in the power system to handle sudden peak loads. This helps to overcome the limitation highlighted for ECMS strategy, where battery utilization considers only instantaneous conditions, which may result in the potential problem in ensuring the reliability to meet future unexpected peak load demand.

Overall, the performance of the proposed MPC and ECMS are comparable in terms of fuel efficiency, as shown in Table A.3. The concept of MPC approach on all-electric hybrid vessel is proven, and the proposed MPC strategy provides a potential solution to improve the power system reliability. To improve the performance of MPC strategy, future work can further investigate in weighting factors tuning, determining of input references with improved methods, load prediction, and performance validation on actual experimental setup.

Figure A.3 Performance comparison of MPC vs ECMS approach

Table A.3 Comparison of fuel consumption of MPC and ECMS

	ECMS	MPC
Fuel consumption (Kg)	292.8	285.9
Fuel savings (%)	-	2.36

Appendix B

**Single line diagram for motor control cabinet and power
electronics and DC bus cabinet**