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POWER MANAGEMENT SYSTEMS FOR SHIPBOARD MICROGRIDS

BY
PEILIN XIE

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Power Management Systems for Shipboard Microgrids

by

Peilin Xie

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Curriculum Vitae

Peilin Xie received the B.S. degree in electrical engineering from Beijing Jiaotong University, Beijing, China in 2015, and the M.S. degree from North China Electric Power University, Beijing, China, in 2018. She is currently working toward her Ph.D. degree in Aalborg University, Aalborg, Denmark. Her research interests include virtual synchronous generator technologies, power and energy management system, and load forecasting methods.

Abstract

Currently, traditional fossil fuels are still the primary power resource for maritime transportation, accounting for more than 95% of the fuel consumed by international shipping. With the increasing demand for decarbonization in the shipping industry, efforts shall be made to achieve more fuel-efficient operation. Thanks to the development of power electronics and information technologies, the future ship is trending towards an all-electric ship with electrical propulsion systems, which offers greater flexibility and operational efficiency, yet makes the vessel more vulnerable to variable and fluctuating propulsion loads, leading to unreliable or inefficient operation.

Hybrid energy storage system has proven to be effective in addressing this issue. However, guaranteeing that the hybrid types of energy components can effectively support the high-frequency fluctuations, assist the main gensets, and ensures sufficient energy backup throughout variable sea states and cruising conditions is critical and places additional requirements for power management systems.

Therefore, the objective of the thesis is to ensure the reliable, efficient, and resilient operation of the ship by developing real-time power management systems. To this end, this project starts with an extensive review of existing optimization-based power/energy management system (PMS/EMS) that have been applied to shipboard microgrids. Based on that, the current research status, gaps, and future trends are summarized and discussed. Relative contents are presented in Chapter 2. Nextly, real-time power management systems that are in the centralized arrangement are developed for radially distributed ships. The proposed PMS is optimization-based and determines the optimal power splitting among multiple energy sources by minimizing the instantaneous equivalent fuel consumption of each component. In addition, a load forecasting system is developed that effectively avoids the power tracking delays and enhances the fuel-saving capability by providing real-time and multi-step load forecasting information. Corresponding contents are presented in Chapter 3 and Chapter 4. Nextly, due to the future trend of ships toward larger scales and zonal distributions, a real-time distributed power management system is developed for the zonal multi-microgrid ship. The distributed scheme can significantly reduce computation time and greatly improve system resilience to failure conditions, while maintaining fuel-efficient operation and healthy energy backup throughout the voyage. And relative content is shown in Chapter 5. Finally, the overall summaries and conclusions of the thesis are made and presented in Chapter 6.

To illustrate the efficiency of the proposed strategies, a series of simulations were performed on MATLAB/Simulink, including comparisons with conventional methods, tests under different sea states and cruising conditions, examination under normal and fault conditions, sensitivity analysis, etc. Results prove that the proposed strategy can realize (i) good power tracking performance under highly fluctuating loads, (ii) high fuel-efficiency operation, (iii) sufficient energy backup throughout the voyage, and (iV) enhanced resilience for zonal electrical distribution (ZED)-based ships. The proposed power management strategies are simple in structure and fast in computation, and therefore suitable for further applications.

Resumé

På nuværende tidspunkt er traditionelle fossile brændstoffer stadig den primære energikilde til søtransport og tegner sig for mere end 95% af det brændstof, der forbruges i den internationale skibsfart. Med det stigende krav om dekarbonisering af skibsfarten må der gøres en indsats for at opnå mere brændstofeffektive operationer. Takket være udviklingen af effektelektronik og informationsteknologi bevæger fremtidens skib sig i retning af et fuldt elektrisk skib med elektriske fremdriftssystemer, som giver større fleksibilitet og driftseffektivitet, men som vil være mere sårbare over for variable og svingende fremdriftsbelastninger.

For at løse dette problem er hybride energilagringssystemer en løsning. Det er imidlertid afgørende at sikre, at de hybride typer af energikomponenter effektivt kan understøtte de højfrekvente udsving og yde effektiv støtte til hovedgeneratorerne, samtidig med at de forbliver tilstrækkelig energibackup under varierende sø-og sejladsforhold, og det stiller yderligere krav til energistyringssystemerne.

Derfor er formålet med afhandlingen at sikre skibets pålidelige, effektive og robuste drift ved at udvikle realtidsstrømstyringssystemer. Med henblik herpå starter dette projekt med en omfattende gennemgang af de optimeringsbaserede strøm- og energistyringsstrategier, der er blevet anvendt i mikronet om bord på skibe. På baggrund heraf opsummeres og diskuteres den aktuelle forskningsstatus, mangler og fremtidige tendenser. Det relative indhold er anført i Kapitel. 2. Dernæst udvikles realtidsstrømstyringssystemer, der er i den centraliserede ordning, til radialt distribuerede skibe. Det foreslåede PMS er optimeringsbaseret og bestemmer den optimale strømfordeling mellem flere energikilder ved at minimere det øjeblikkelige ækvivalente brændstofforbrug for hver komponent. Desuden udvikles et belastningsprognosesystem, som effektivt undgår forsinkelser i forbindelse med strømsporing og forbedrer brændstofbesparelseskapaciteten ved at give oplysninger om belastningsprognoser i flere trin i realtid. Det tilsvarende indhold præsenteres i Kapitel. 3 og i Kapitel. 4. På grund af skibes fremtidige tendens til større skala og zonedistribution udvikles der dernæst et distribueret realtidsstyringssystem til det zonedistribuerede multi-mikronet skib. Den distribuerede ordning reducerer beregningstiden betydeligt og forbedrer i høj grad systemets modstandsdygtighed over for fejlbetingelser, samtidig med at skibets brændstofeffektive drift og sunde energibackup opretholdes under hele rejsen. Og det relative indhold er vist i Kapitel. 5. Endelig foretages de overordnede sammenfatninger og konklusioner af afhandlingen og præsenteres i Kapitel. 6.

For at demonstrere effektiviteten af de foreslåede strategier blev der udført en række simuleringer i MATLAB/Simulink, herunder sammenligninger med konventionelle metoder, test under forskellige søforhold og sejladsbetingelser, undersøgelse under normale og fejlbehæftede forhold, følsomhedsanalyse osv. Resultaterne viser, at den foreslåede strategi kan sikre i) god effektsporing under stærkt svingende belastninger, ii) høj brændstofeffektivitet, iii) tilstrækkelig energibackup under hele rejsen og iV) øget modstandsdygtighed for zone-elektrisk distribution (ZED)-baserede skibe. De foreslåede strategier for energistyring er enkle i deres struktur og hurtige i deres beregningshastighed, og de er derfor egnede til yderligere anvendelser.

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Chapter 1 Introduction

1 Research Background

1.1 Marine Transportation and Emission Regulation

Shipping is a critical part of the global economy. It is by far the most environmentally friendly mode of transportation compared to aviation, railway, and road transport. It is also the primary way of long-distance transport, accounting for approximately 80% of the world's trade [1], but only 11% of the global CO_2 emissions from transportation, as can be seen from Fig. 1.1.

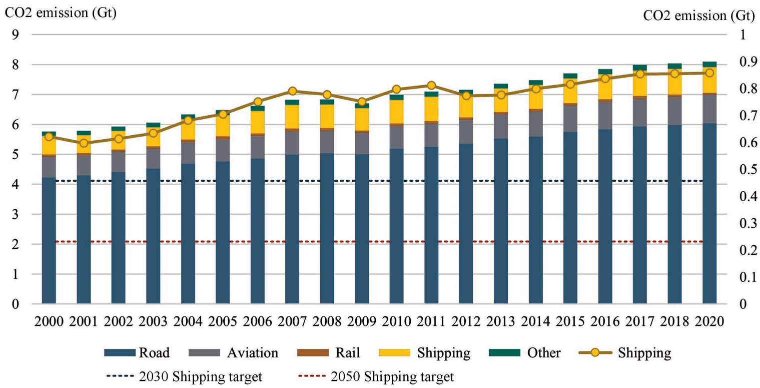

Fig. 1.1: Global CO_2 emissions in transport by mode [2]

Currently, more than 95% of ships still use traditional fossil fuels as their primary source of power. Although low-carbon resources such as methanol have emerged and been adopted in marine transportation since 2015, the percentage is still quite small, as shown in Fig. 1.2. The utilization of fossil fuels produces significant amounts of greenhouse gases (GHGs) and other pollutants. According to the ambitions of the International Maritime Organization (IMO), the carbon intensity of shipping should be reduced by at least 40% by 2030, and 70% by 2050, compared to 2008 levels [3], as can be seen from Fig.

1.1. Achieving this goal will require revolutions in the shipping industry, alternation of fuel economy, development of control and management systems, and efforts across the broader shipping ecosystem. By doing so, the ships of the future are developing toward being more electrical, efficient, green, integrated, autonomous, and intelligent.

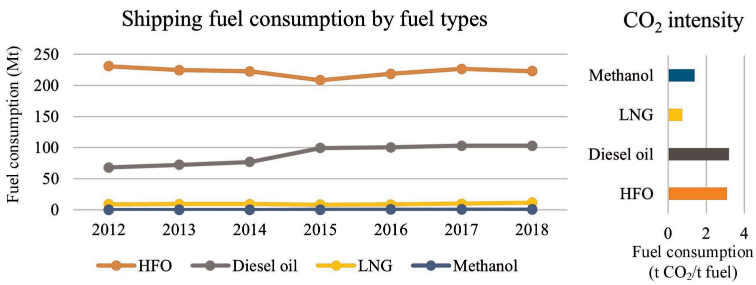

Fig. 1.2: International marine fuel consumption by fuel type [4, 5]

1.2 Towards Future Ships: All Electrical Ship

Due to the advantages of flexibility in space and weight allocation, enhanced operating life, increased survivability and maintainability, and high operational efficiency, the all electrical ship (AES) concept is receiving increasing interest and is becoming a standard form of high-powered demand vessel [6]. The promotion of AES requires a series of corresponding technical and platform support. Development in power electronics, information technology, and electrical propulsion technology has motivated the research of integrated power systems (IPS) and thus has made it possible to rebuild a shipboard microgrid with an all-electric architecture [7]. A standard IPS comprises a set of modules that together provide the basis for design, procurement, and support, including: the power generation module (PGM), energy storage module (ESM), power conversion module (PCM), power distribution module (PDM), power control module, propulsion module, and onboard loads [8], as can be seen in Fig. 1.3. The high degree of modularity of the shipboard power systems allows it to be flexibly assembled and tested, and to operate at a lower cost, with lower noise, higher survivability, and less fuel consumption [9].

Propulsion System

The major difference that separates AES from the traditional ships is that everything on broad in AES will depend on electric power. The most typical one is the electrification of the ship's propulsion system.

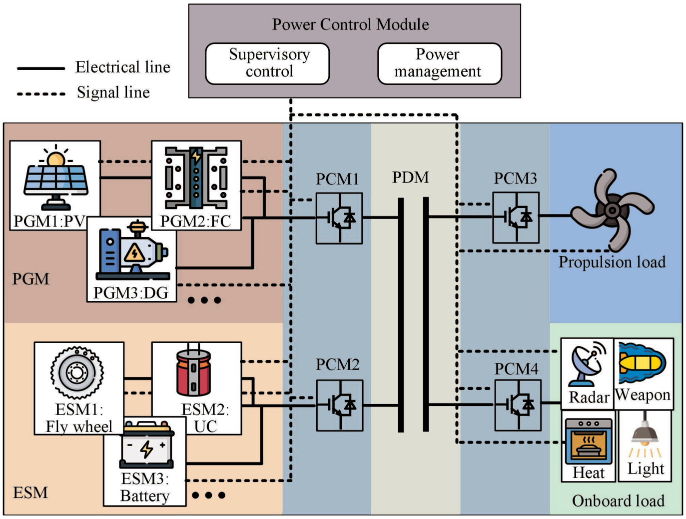

Fig. 1.3: Integrated power system diagram [10]

Fig. 1.4 gives the overall structures of different types of ship propulsion system. In a traditional diesel-driven ship, the propeller and the prime mover (diesel engine or gas turbine) are directly connected through a reduction gear, which limits the range of engine rotation speeds and can lead to low fuel efficiency and high emissions at low rated loads. Conversely, electrical propulsion system replaces the prime movers with motors that can be DC or AC driven and are supplied directly from the main power system. In this way, more flexible operation, higher fuel efficiency, and reduced maintenance cost can be guaranteed. Furthermore, to better take advantage of both traditional mechanical and electrical propulsion systems, hybrid propulsion system has been developed and applied to the ships that frequently operate at low speeds, such as naval vessels, towing vessels, and offshore vessels [11]. Hybrid propulsion system consists of a mechanical section that operates primarily at high load demands and an electrical section that supports the propulsion load at low speeds. However, to better benefit from the two schemes, more pressures are laid on the related control strategy design.

Power Generation and Energy Storage System

Due to the increasing demands for decarbonization of marine transportation, efforts have been made either to improve the fuel efficiency of the traditional fossil fuel-consumed gensets or to replace traditional diesel generators with more alternative and low-carbon fuels, such as wind [12], photovoltaic panel [13], bio-based fuels (including biogenic, biodiesel, and algae) [14], liquid

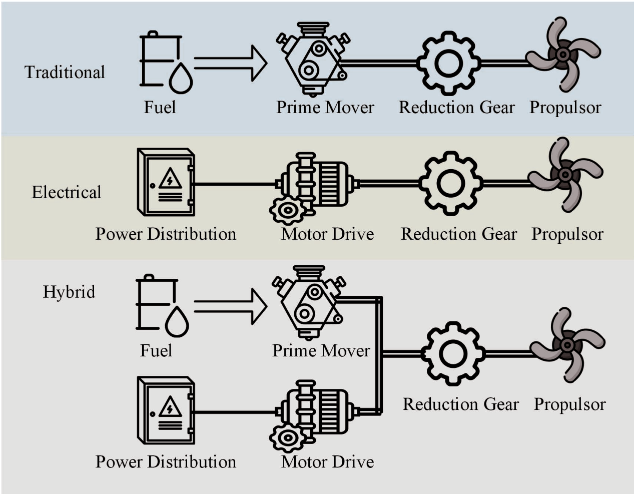

Fig. 1.4: A comparison of traditional, electrical, and hybrid propulsion systems [11]

natural gas [15], hydrogen [16], and heavy fuel oil [17, 18].

However, as the penetration of these renewable energies grows, despite their benefits in terms of reduced emission, they lead to increased investment costs and greater vulnerability to uncertainty, which makes the energy storage system a necessity [19]. Among all, due to the characteristics of high energy density, portability, ease of use, and variable storage capacity, batteries have been most commonly adopted in marine applications. In addition, considering the changeable sea states, fluctuating propulsion load conditions, and the pulsating onboard load demands, other types of energy storage components such as ultracapacitors and flywheels have been found to be effective in supporting high-frequency loads and enhancing the lifetime of main generators when used in combination with batteries, leading to the application of hybrid energy storage systems [20].

Predictably, future shipboard power systems will comprise multiple power sources and different types of energy storage systems, and thus will require advanced supervisory and power control systems to coordinate the power flow over the IPS.

Distribution Architecture

As for the electrical layout, Fig. 1.5 and Fig. 1.6 show the two main distribution architectures employed in the design of AES: radial and zonal layouts, respectively.

Radial power distribution is the most adopted and studied, and the most mature type of shipboard power system (SPS) due to its structural simplicity and cost effectiveness. However, due to the future trend of ships towards larger scales and increasing requirements for survivability, reliability, and efficiency, zonal electrical distribution is receiving rising interest and is becoming a future standard [21]. In zonal distributions, the power systems are divided into several zones that are connected through bus-tie switches. This structure allows each zone to supply its local loads independently, support neighbors, and even be disconnected from the main grid if necessary, thus increasing operational flexibility and resilience to faulty occasions. However, it cannot be ignored that the complexity increases, and thus requires revolutions of the power control system to maintain a stable, safe, and efficient operation.

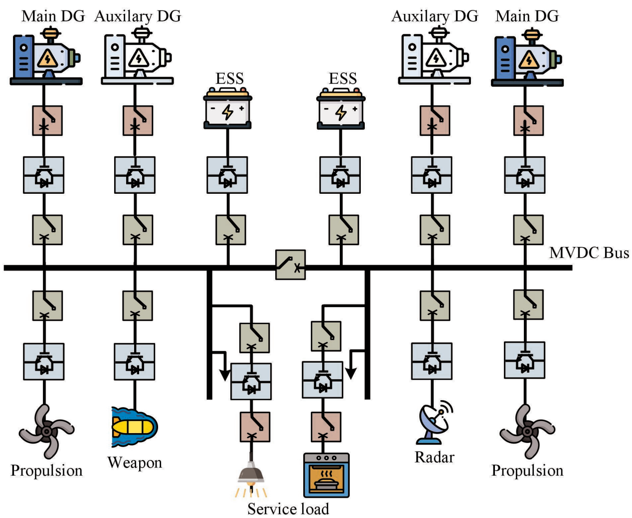

Fig. 1.5: An example of DC radial distribution system [22]

Control System

For the purpose of coordinating multiple types of power resources and hybrid energy storage systems, and meeting changeable load demands, power control system is essential and has proven to be effective in maintaining system stability, high efficiency, low capital investment, and green operation. According to different control objects, objectives, and time scales, the current control strategies can be classified by a hierarchical framework as shown in Fig. 1.7.

The primary layer focuses on controlling the inverters to realize the preliminary power sharing, as well as current and voltage regulation. By constituting decisions from the upper layer, the secondary layer coordinates be-

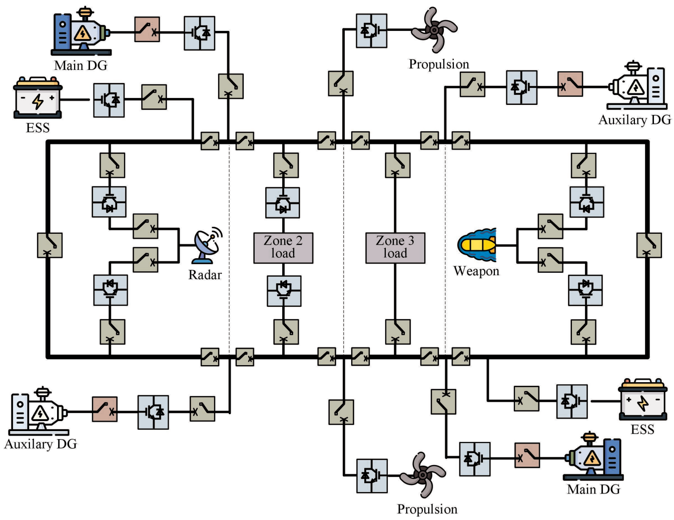

Fig. 1.6: An example of DC zonal distribution system [22]

tween the power generators, the energy storage systems, and the loads to maintain the bus voltage, frequency, and power quality. The tertiary layer consists of complex decision-making processes such as energy management and voyage scheduling to realize objectives such as high operational fuel efficiency, low cost and carbon emissions, and extended components lifespan. Decisions are made based on real-time data gathered from the lower layer, historical statistics, or the predicted future information, and the generated optimized commands are then sent to the lower layers.

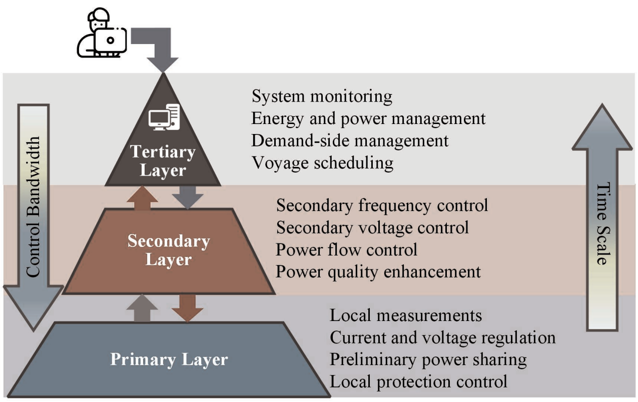

Fig. 1.7: The hierarchical control scheme of SPSs [23, 24]

2 State of The Art of Maritime Power and Energy Management Systems

A shipboard power system can be treated as a mobile microgrid, typically operating in island mode at sea and grid-connected mode when in port [25]. Ensuring that ships can perform their cruising duties economically, environmentally friendly, and reliably is a constant necessity for marine transportation. To achieve this goal, PMS/EMS is the key, which has proven to be effective in many other power systems such as terrestrial, vehicle, residential, and aircraft [26]. The resemblances between the SPS with the others in network architecture, island operation, and the use of power electronic devices allow the traditionally developed PMS/EMS to be easily extended to marine applications. However, there remains some other issues to be further considered in the design of shipboard PMS/EMS, such as limited space onboard, increasing use of renewable energy sources, the presence of large dynamic loads, and especially the large percentages of propulsion loads which has a high dependence on waves, weather, wind, and cruise plans. Negative effects such as volatility and uncertainty therefore drive further research.

2.1 Research Objectives of Shipboard PMS/EMS

According to different research objectives, current studies on shipboard PMS/EMS can be roughly categorized into three main aspects: management on the generation side, management on the demand side, and management on the vessel voyage scheduling, as shown in Fig. 1.8.

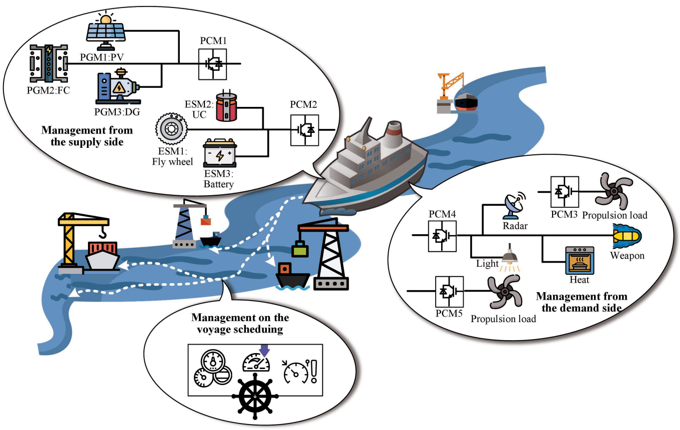

Fig. 1.8: Three main research objectives for shipboard PMS/EMS

Management from the Supply side

The primary target of PMS/EMS that falls into this category is to regulate the behavior of multiple power generations and energy storage systems to fulfill the power demand with high efficiency and reliability but at the least cost. Current studies are mostly conducted with the following objectives:

1. Fuel economy improvement: Referring to maintaining the high operational fuel efficiency of power generators and reducing the overall fuel consumption. Achieving this goal usually requires advanced generation planning according to the historical load profiles [27–29], as well as the most fuel-efficient power allocation between the generators and energy storage systems in real-time [30–33].
2. Economical investment reduction: Economical costs include primarily the costs of facility installation, operation, fuel consumption, start-up and shut-down, and maintenance. In order to reduce the economical investments, comprehensive assessments of the shipboard power system in terms of financial costs are required and conducted in the literature, ranging from the selection of component types and optimal sizing of them [34–37] to the economic energy dispatch between generation and energy storage units [38–40]. Particularly, for ships that adopt renewable energy sources, fuel cells, and batteries as energy supplies, degradation cost is also a key factor in evaluating the overall financial investment [35, 41].
3. GHG emission minimization. GHG emission is one of the major concerns considered in the related literature, and it can be evaluated by two indicators, the Energy Efficiency Design Index (EEDI) and the Energy Efficiency Operation Index (EEOI), which are defined by IMO to quantitatively calculate the GHG emission according to the fuel consumption, transportation work, cargo weight, distance, operational state, etc. [42–44].
4. Automatic generators synchronizing and system restoration. Guaranteeing an adequate energy supply and a fast recovery ability from failures and blackout is essential to shipping stability and reliability. In response to that, generators are required to start-up, shut-down, and operate at fast synchronization speeds, with proper quantities, and in a reasonable sequence under the guidance of the PMS/EMS [24].

Management from the Demand Side

Due to the different shipping status during sea cruising and port berthing, different requirements and management objectives are imposed on the demand-side management.

When the ship is at sea, it can be considered as an island microgrid where the primal target is to maintain a balance between power supply and demand. Considering that propulsion load accounts for a large proportion of the onboard loads, its characteristics of high volatility, variability, and great dependence on environmental states and human operations place higher requirements on the energy generation and storage systems. Typically, the total installed capacity of generation is greater than the system maximum demand of the system. However, the large uncertainty of the navigation environment and the increasing penetration of renewable energy resources onboard certainly raise the risk of the power supply and demand imbalance, making demand-side load management an essential task to rebalance the power system in case of supply inefficiencies. A typical solution is to categorize the onboard loads into critical, semi-critical, and non-critical loads based on their importance in maintaining the system normal operation, and to shed these loads in order of priority in case of contingencies such as loss of generation or increased load, as in [45–48].

While for the cases when ships are in the port, shore-side grid power (called cold-ironing) is available, and thus bidirectional power flow is enabled between the ship and the grid [49]. Correspondingly, with the energy support from the shore, the primal goals of demand-side management shift to improving the efficiency of ship operation, reducing fuel costs and GHG emission, and even enhancing grid-side security and efficiency. As in [50–52], by evaluating the annual load profile, the electricity price on shore, and the possible fuel consumption onboard, greener and lower-cost ships can be achieved.

Management on the Vessel Voyage Scheduling

A ship is required to fulfill its cruising task by punctually arriving at the transit or terminal ports at safe speed throughout the voyage [53]. The navigation speed, direction, and distance of a ship are directly driven by the propulsion system. With the increasing electrification of shipboard propulsion systems, more flexible and controllable operation is enabled, however the controlling complexity increases as well. Any adjustments to the cruising schedule would have a direct impact on the electrical system, and thus influences the results of facility sizing and installation, generation scheduling, and energy dispatching. Therefore, voyage scheduling is one essential part not only in guaranteeing compliant cruises but also in maintaining economic and environmental operations.

Current studies with this target can be roughly grouped into two aspects according to the different stages of energy management. The first is typically formulated as joint optimization problems including the optimal voyage scheduling and generation scheduling, subjected to navigation limits such as cruising speed, arriving time, and voyage distance, as well as conventional electrical limits such as power balance, maximum power and energy capacity, energy reservation, etc. [37, 54–56]. While the latter separates the problem into voyage scheduling and energy dispatching respectively. By optimizing the vessel cruises in advance with updated shore-side information (e.g., electricity prices), ship operators are allowed to adjust cruise schedules to find the most economical transit ports and berth time. Nextly, optimal energy dispatching is performed based on the optimized cruise plans to further improve the ship operational efficiency [57–60]. It is worth to be noted that although the latter takes into account information not only from the ship itself but also from the harbors, it is only applicable in cases where slight variations in cruising schedules are allowed. For those with fixed and strict cruising routines and timesheets, the former is more efficient.

2.2 Management Strategies of Shipboard PMS/EMS

The commonly used methods for shipboard PMS/EMS can be broadly classified as rule-based, optimization-based, and learning-based methods. Tab. 1.1 gives the summary of these methods in terms of their features and applicable areas.

Rule-based

The Rule-based method is determined based on human intelligence and experience, and it controls the operation behavior according to a series of predefined priorities, tables, or flowcharts. Typically, it can be classified into fuzzy rule control and deterministic rule control [61].

Fuzzy rule control is performed through the following three steps [62]:

1. Fuzzification: Converting classical control and output variables into fuzzy variables.

2. Fuzzy Inference Process: Deriving the fuzzy output according to the fuzzy control rules.

3. Defuzzification: Converting fuzzy outputs back to classical variables.

By combining with other advanced methods such as optimization methods, intelligence methods, and prediction methods, fuzzy rule control is able to gain better performance, larger degrees of freedom, and greater adaptability to the real-time applications [63].

Deterministic rule control is developed based on a series of predefined 'If-Then' type of rules that dependent on human expertise and are implemented through look-up tables or state charts [63]. And it can be further

Table 1.1: Summary of all PMS/EMS strategies: classifications and features

Strategies	Advantages and disadvantages	Applications
Rule-based	**Advantages**: 1. Simple structure 2. Easy to implement 3. Less computing effort 4. Robust **Disadvantages**: 1. Require more tuning effort 2. Require expert 3. Can not guarantee optimum results 4. Change significantly for different topology	Real-time
Optimization-based	**Advantages**: 1. Optimal or suboptimal results 2. Suitable for different topologies **Disadvantages**: 1. Require more computation efforts 2. Hard to solve complex system	Real-time/global
Learning-based	**Advantages**: 1. Not require pre-knowledge 2. High robust **Disadvantages**: 1. Difficult in accurate data minning 2. Time consuming 3. Great pressure for computational resources	Real-time/global

sub-divided into thermostat control, state machine control, power follower control, gliding-average control, etc. as shown in Tab. 1.2 [64].

Comparatively, although fuzzy rule-based methods may consume more computational resources than deterministic methods, the greater robustness and control flexibility make them more suitable for dynamic situations, motivating increasing research interests. In addition, basically all rule-based methods are based on human experience and are built according to their own system configurations. The limitations in human decision-making, as well as changes in system topology, would directly affect the effectiveness of rule-based methods. However, the rule-based methods are still efficient in real-time PMS/EMS applications due to their advantages in fast processing speed, nice performance, and simple structures, and are always used as benchmarks for evaluating other types of methods.

Table 1.2: Summary of rule-based methods: available control strategies and features

Logic types	Commonly used strategies	Advantages and disadvantages
Fuzzy	1. Conventional fuzzy strategy [65–69] 2. Fuzzy adaptive [70, 71] 3. Fuzzy optimization [72–76] 4. Fuzzy predictive [77]	**Advantages**: 1. Unique in handling both numerical data and linguistic knowledge 2. Strong robustness to uncertainties and disturbances 3. Highly adaptable and easy to be tuned **Disadvantages**: 1. Relatively needs more computing effort and longer processing time
Deterministic	1. Thermostat (on/off) control [32, 78] 2. State machine control [79, 80] 3. Power follower control 4. gliding-average control	**Advantages**: 1. Simple structure and easy to implement 2. Low computational requirements **Disadvantages**: 1. Not accurate enough 2. Sub-optimal results

Optimization-based

In contrast to rule-based approaches, optimization-based strategies seek to provide optimal or suboptimal solutions through analytical or numerical optimization algorithms [81]. Depending on different control objectives, results, and control time scales, methods can be roughly categorized into global planning and real-time scheduling, the features of which are shown in Tab. 1.3.

The global-planning based method is usually adopted to provide guidance in terms of facility selecting, sizing, energy dispatching, and voyage scheduling in ahead of time based on whole system information, historical load profiles, or cruising plans. It is supreme in handling large-scale optimization problems with the ability to acquire global optimum solutions, or multi-objective problems even with conflict targets. Consequently, more computational resources are required and therefore it is not suitable for real-time applications. Conversely, the real-time optimization method gathers instantaneous information, such as load demand, state of charge (SOC), cruising states, etc. to solve the optimization problem and provide real-time guidance to realize a stable and efficient operation. However, due to the lack of global information and long-term perspective, real-time optimization cannot guarantee the optimality of the results, which makes rule-based methods and global-planning based optimization necessary in benchmarking the performance of real-time optimization.

Table 1.3: Summary of optimization-based methods: available control strategies and features

Optimization types	Objectives	Optimality of results	Time scales	Historical load profile
Global	1. Onboard facility sizing 2. Energy dispatching 3. Routine scheduling	Optimal	Long-term	Require
Real-time	1. Real-time power splitting 2. Load shedding 3. Voltage maintaining	Suboptimal	Short-term	Not require

Learning-based

The shipboard power system is a complex system with great uncertainty and variability due to its high dependence on seasons, weather, sea conditions, human decisions, and political, social, and economical factors. In addition, the increasing penetration of renewable energy resources further exacerbates these characteristics. The aforementioned methods are mostly developed based on human expertise and predefined models and may lose their accuracy when encountering dynamic changes or when there are frequent interactions between human behavior and the power system. Therefore, data-driven approaches that are effective in data evaluation, processing, and analysis are key to guaranteeing ship reliable and efficient operation. Considering the huge amount of data involved, it facilitates the research of learning-based methods in shipboard PMS/EMS applications. Learning-based methods are advantageous in processing complex and large-scale data, and current studies generally focused on the following aspects:

1. Forecasting: Including energy generation forecasting, loading cycles forecasting [82], shore-side electricity price forecasting [83], propulsion load forecasting [84], navigation environment forecasting [85], etc.. By continuously collecting information from a long-term time horizon, the predicted data are provided to the energy management systems to realize the near-optimal performance without pre-known of future information.

2. Decision making: Referring to finding the optimal decisions based on large numbers of observations and the reward signals. Researching targets include the optimal power splitting [84, 86], sizing optimization of onboard energy resources [87], suppressing the power fluctuations [35], etc.. By adopting learning-based methods instead of the traditional methods, great robustness and the optimality of results can be expected even under highly dynamic, complex, and unknown situations. However, the big historical statistics and the time-consuming data

training process put greater pressure on the computational resources, which may cause problems for the real-time applications.

3 Challenges

3.1 Highly Load Fluctuations

The ship propulsion system is the primary energy consumer of AES and needs to be satisfied to guarantee a normal operation. However, the inherent interaction of the propeller with waves introduces fluctuation in thrust and torque and thus would bring negative effects to both electrical and mechanical systems. As shown in Eq. (1.1), (1.2), and (1.3), the propeller thrust T_{prop}, torque Q_{prop}, and power P_{prop} are influenced by many factors including the motor shaft speed n_{prop}, water density ρ, propeller diameter D, non-dimensional coefficients K_T, K_Q that stand for the open-water characteristics of propeller, and propeller loss factor β [88].

$$T_{prop} = sign(n_{prop})\beta\rho n_{prop}^2 D^4 K_T \tag{1.1}$$

$$Q_{prop} = sign(n_{prop})\beta\rho n_{prop}^2 D^5 K_Q \tag{1.2}$$

$$P_{load} = 2\pi n_{prop} Q \tag{1.3}$$

β is sensitive to the behavior of propeller in-and-out-of water. For the purpose of quantitative assessment, it is usually expressed by propeller submergence ratio h/D, as can be seen from Eq. (1.4) [89],

$$\beta = \begin{cases} 0 & h/D < -0.48 \\ 1 - 0.675 \times (1 - h/D)^{1.258} & -0.48 \leq h/D \leq 1.3 \\ 1 & h/D > 1.3 \end{cases} \tag{1.4}$$

where h is the propeller submergence depth.

The interaction between wave collision and propeller behavior leads to fluctuations in propulsion load demand, which will be even more severe under extreme sea conditions. If not handled well, the negative effects would pose a potential threat to the stability of the SPS, damage the lifespan of the mechanical system, and reduce operational efficiency [90]. Therefore, efforts shall be made to mitigate the negative effects of the propulsion load fluctuation. To do so, specific research has been conducted such as thruster controller designing [91, 92] or, more generally, hybrid energy storage systems [90, 93–95]. Unlike the onboard ship service load, the fluctuations induced by propulsion loads are periodical and high-frequency in nature, causing great pressure on the power generation system. The utilization of two different kinds of energy storage systems (typically including high power-density devices and high energy-density devices) would effectively address those problems.

However, the integration of hybrid energy systems makes the electrical power system more complex, increasing the difficulty of analyzing, controlling, and optimizing. To ensure high operational efficiency while guaranteeing adequate energy supplement, the power flow between multiple energy resources needs to be carefully regulated, which requires the further development of real-time power management systems.

3.2 Real-time Load Forecasting

Although shipboard PMS and EMS have proven to be essential in improving system efficiency, reliability, and resilience, their performance depends largely on the knowledge of future load, which makes load estimation and forecasting necessary.

Current studies on load forecasting are mostly designed for long-term prediction, require large amounts of historical data, and are mostly developed based on artificial intelligence methods [96–98]. With sufficient training process, these methods can effectively handle the large-scale problems with highly robust and reliability and are especially suitable for the prediction of regular or seasonable load profiles. Provided with the weekly, monthly, or yearly future load profile, the global-planning based methods are able to make wiser decisions. However, such methods require great computational resources for data statistics and training, and therefore have to be conducted offline and might not be suitable for the highly dynamic and changeable real-time applications.

Considering the unpredictable sea states, variable ship sailing speed, and changeable cruising conditions, the propulsion load can exhibit different characteristics and would be hard to accurately forecast using the up-mentioned strategies. In addition, the fluctuations induced by sea waves further increase the difficulty of prediction, compensation, and suppression.

Although load forecasting is not mandatory for real-time power management systems, pre-knowledge of near-future load information will certainly provide PMS with a longer-term perspective and thus improve management performance. Furthermore, today model predictive control (MPC) has been found to be widely adopted in real-time power management systems [90, 99–102], whose key idea is to acquire more informed decisions by allowing the system to look a few steps ahead. Therefore, information on the future load over the prediction horizon is necessary. Current studies addressing this problem either adopt fixed load values with the expectation that the load will not change too much during the prediction horizon, or use statistical methods such as linear prediction. The former is easy to be implemented in real-time due to fewer computing efforts, however, fails to capture the dynamic behaviors of the propulsion loads and thus may lead to unsatisfying results. While the latter can be more suitable for fluctuating situations however consumes more computational time and thus needs to be carefully addressed when applied in real-time. Due to the current research gap in this area, more research efforts shall be made to develop efficient and high-accuracy real-time load forecasting methods to assist PMS in decision making.

3.3 Power Management System in Distributed Scheme

According to different control arrangements, commonly developed power and energy management systems can be categorized into centralized, distributed, and decentralized as shown in Fig. 1.9.

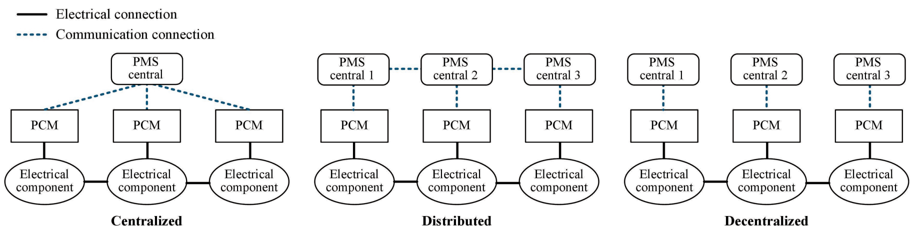

Fig. 1.9: The control scheme of power/energy management system for SPS [103]

Most currently developed PMS/EMS are in centralized arrangements that enable global optimum solutions, however require comprehensive knowledge of the entire marine system and suffer from risks of single-point failures. Furthermore, these problems would become more severe when traditional centralized PMSs are applied to future shipboard power systems that are in larger scales, with greater injection of renewable energy resources, and have different distribution topologies. The increased amount of computational effort will decrease the effectiveness of the traditional centralized management strategies, making them unsuitable for real-time applications.

To solve this problem, the power management system developed in the distributed scheme is a possible solution and is receiving increasing research interest. After decomposition, the global optimization problem can be divided into sub-problems, which are resolved by sub-centers with information communications. Computing efforts can be significantly reduced and results in lower pressure for real-time applications. In addition, the distributed scheme allows for more flexible control of the system and thus enables more resilient and reliable operations. However, it is worth to be noted that better solutions require better knowledge of the system states and more information exchanges, which results in increased signal transmission time and more computational resources. The trade-off between optimal decisions and computational efforts needs to be handled carefully. Meanwhile, the applications of different electrical topology such as ZED-based SPS provide both opportunities and challenges for the controlling, monitoring, and management. Due to the current research gap and the future trends towards green, efficient, and economical ships, a practical and reliable distributed power management system is worthwhile.

4 Thesis Objectives

The major target of the thesis is to realize a fuel-efficient, reliable, and resilient shipboard power system with consideration of highly fluctuated propulsion load. To be more specific, several sub-objectives are considered:

1. Improve the reliability and fuel efficiency of shipboard power system under high fluctuated propulsion loads, including:
   - Guaranteeing good power tracking performance under high-frequency propulsion load fluctuations.
   - Realizing high fuel-efficiency power splitting between multiple energy resources in real-time with absence of future load information.
   - Ensuring sufficient energy backup throughout the whole cruise in different sailing modes.
   - Realizing accurate short-term load forecasting with real-time application capabilities.
2. Extend the centralized power management strategies to distributed arrangements to better suit large-scale and zonal distributed ships, including:
   - Developing distributed power management framework capable to be applied to zonal electrical distribution-based ships.
   - Guaranteeing high fuel-efficiency operations and adequate energy reservations.
   - Enhancing the resilience of shipboard power system facing faulty conditions.
   - Simple structure, fast convergence speed, high efficiency, and capability to be applied in real-time.

5 Thesis Contributions

In order to achieve the above objectives, power management systems are studied with a particular focus on optimization-based and real-time applications. The summary of the contributions is listed below:

1. A thorough review of current studies on optimization-based power/energy management systems developed for SPS, which is the main content of Paper 1, including:
    - The summary and classification of the existing optimization-based shipboard PMS/EMS.
    - The summary of the most concerning topics and objectives.
    - The comparison of different methods and the discussion about their suitable applications.
    - The discussion of current research gaps and future researching trends.
2. A real-time predictive optimization algorithm designed for hybrid energy powered ship, which is the main content of Paper 2, and the proposed method can ensure:
    - High power tracking performance under highly fluctuated propulsion loads.
    - Real-time power splitting capability with consideration of fuel efficiency.
3. An improved centralized real-time two-layer power management system that guarantees an efficient and reliable operation throughout the voyage, which is the main content of Paper 3 and includes:
    - A hybrid rule-based and optimization-based scheme that guides the on/off operations of main gensets and the optimal power split between them.
    - A multi-step load forecasting method that has fast computing speed, high accuracy, and capability of multi-step prediction to eliminate the power tracking delays and assist the MPC with future load information for wiser decisions.
    - The comparisons and verification under multiple sea states, and different sailing speeds and cruising conditions.
4. A distributed multi-layer real-time power management system that is targeted especially for zonal electrical distribution-based ships with the idea of improving fuel efficiency and enhancing system resilience, which is the main content of Paper 4, and includes:

- A three-layer framework that hybrids rule-based and optimization-based methods to filter the load fluctuations, estimate the SOC condition of the energy storage system, and distribute the load in a high fuel-efficiency way.
- A distributed scheme that allows zonal communication and support to achieve improved computing efficiency, reliability, and resilient operation.
- A distributed optimization algorithm that requires less transmission information, has a fast convergence speed, and can be easily applied in real-time.
- Evaluation, simulations, and discussion under different sea conditions, cruising modes, normal and faulty situations to evaluate the effectiveness of the proposed PMS with regards to fuel efficiency, computing speed, and fault supporting ability.

6 Thesis Outlines

The thesis is presented in six chapters and the outline is shown below:

Chapter 2 presents the major content of Paper 1, which was published in IEEE System Journals in 2022. It gives a review of the existing studies on optimization-based power and energy management strategies.

Chapter 3 presents the major content of Paper 2, which was published in Energy Reports in 2021. It illustrates the main causes of the load fluctuations and proposes an MPC-based real-time optimization algorithm to mitigate their negative effects.

Chapter 4 presents the major content of Paper 3, which was accepted by IEEE System Journals in 2022. It proposed a real-time two-layer power management system to enhance the shipping fuel efficiency and system reliability through different sea states, sailing speeds, and cruising conditions.

Chapter 5 presents the major content of Paper 4, which was published in Applied Energy in 2022. It develops a real-time power management system for large-scale zonal ships and builds it in a distributed way. By doing so, improvements in fuel efficiency, reliability, and resilience are obtained.

Chapter 6 gives the conclusion and future work.

Chapter 2 Review of Maritime Optimization-based PMS/EMS

Main Contents are as Paper 1: Optimization-Based Power and Energy Management System in Shipboard Microgrid: A Review

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IEEE Systems Journal, vol. 16, no. 1, pp. 578-590, 2022

Abstract

For the purpose of coordinating different types of onboard energy resources, supporting dynamic and fluctuating loads, and improving the system performance economically, environmentally, and technically, power/energy management systems are common choices. Due to the advantages in obtaining optimal solutions and handling multiple or even conflicting objectives, optimization-based methods are widely adopted and researched. In order to gain a better understanding of the current research status and have a clearer clue for future work, a review of shipboard optimization-based PMS/EMS is presented.

1 Summary of the Contribution

- Summaries and analyses of the current research objectives and constraints are presented, providing a general understanding of research interests and future directions.
- An overview of the existing optimization-based power/energy management strategies are described and classified into two aspects: global planning and real-time optimization.
- Some significant and typical management strategies are studied and introduced separately.
- Current research gaps and future trends are discussed and presented.

2 Main Work

2.1 Generally Considered Objectives and Constraints

The key idea of an optimization-based power and energy management system is to find the optimal solution with minimum cost while subjected to the predefined electrical, mechanical, or environmental constraints. Therefore, the formulation of the objective functions and constraints is a critical and primary consideration. The summary and description of the commonly considered objectives and constraints are presented in Tab. 2.1 and Tab. 2.2, respectively. It is worth noting that, in practice, instead of pursuing just one optimization goal, commonly there would be multiple or conflicting goals and thus trade-offs and compromises are required. [104–107].

Table 2.1: Summary of optimization-based shipboard PMS/EMS strategies: Objectives

Objectives	**Description**
Fuel consumption minimization	• Mainly includes reducing fuel consumption during generation, start-up, and stand-by. • Encourages the generators to work at optimal fuel efficiency points. • Pursues optimal power splitting between multiple onboard energy resources.
Environmental footprint reduction	• Mainly refers to reducing GHG emissions. • Generally evaluated by two key factors: Energy Efficiency Operation Indicator, and Energy Efficiency Design Indicator.
Economical cost minimization	• Mainly includes financial expenditures associated with the operation, investment, and maintenance. • Mostly evaluated by net present cost, however, the annualized cost and life cycle cost are also important factors.
Equipment selection optimization	• Typically refers to the optimal selecting, composition, and sizing of onboard equipment given consideration of limited vessel space, load requirements, as well as economical and environmental factors. • Commonly in conjunction with other objectives, and requires compromise with economical, environmental, or physical constraints.
Navigation endurance maximization	• Aims to improve shipping cruising capabilities. • Requires evaluation and management between ship cruising plans, energy reservation, energy storage system capacity, and remaining fuel volume. • Rarely been discussed.

Table 2.2: Summary of optimization-based shipboard PMS/EMS strategies: Constraints

Contraints	**Description**
Power and energy balance	The primary and most important constraint.
Power quality restraints	Typically refers to the voltage stability limitations ($\pm$5%) and frequency stability limitations ($\pm$3%).
Restraints related to power plants	Mainly limits the generator loading, power ramp rate, operation and stand-by time, spinning reservations, etc.
Restraints related to ESS	Mainly limits the state of charge, depth of discharge, power, and energy capacity of the energy storage system.
Environmental restraints	Regulations made by International Maritime Organization; Not mandatory but voluntarily considered to achieve green navigation.
Voyage restraints	Mainly limits the shipping speed, travel distance, quantities of loads carried, etc.
Auxiliary system restraints	Includes limitations on heat balance, heat loss, and temperature.

2.2 Global Planning-based Power and Energy Management Strategies

As discussed in Chapter 1, current optimization-based PMS/EMS strategies that have been developed for SPS can be roughly classified into two categories: global-planning and real-time according to different control objectives, results, time scales, and requirements for historical load profiles.

Global planning-based strategies typically involve a large amount of information and require great computational resources to acquire the global optimal solution. They are mostly used offline to solve complex and large-scale optimization problems or to benchmark the performance of real-time based strategies. Existing methods that fall into this category can be generally categorized into classical and heuristic methods, and the commonly adopted methods are summarized and introduced in Tab. 2.3. Classical methods are comparably more suitable for problems with simple structure, small scale, and less number of variables. They can guarantee the optimality of the results, however, have difficulties in solving highly nonlinear, complex, and large-scale optimization problems owing to the great computational resources required. In cases where it is computationally expensive to use the classical methods and acceptable for approximate solutions, heuristic methods are effective alternatives since they allow a faster exploration of the solution space, even if this means finding the suboptimal solutions. Sometimes, in order to guarantee both the optimality and computational efficiency, hybrid methods that combine the two kinds are developed and adopted [108–110].

2.3 Real-time Power and Energy Management Strategies

Different from the global-planning based power and energy management strategies, real-time optimizations do not require the prior knowledge of historical or future load profiles and acquire the optimal solution from instantaneous information obtained through continuous evaluation of the system. Instead of global large-scale optimization problems or early-stage organizing problems, real-time optimizations are more efficient and effective in solving instantaneous optimization problems to achieve improved fuel efficiency, system stability, and economy under high dynamics and uncertainties. The most popular strategies are introduced in the following subsections.

Equivalent Consumption Minimization Strategy

Equivalent Consumption Minimization Strategy (ECMS) is one of the most efficient ways to achieve instantaneous fuel-efficient power splitting. The key idea of ECMS is that in a multi-power supplied system (taking diesel generator and energy storage system (ESS) as an example), ESS can be treated

Table 2.3: Summary of global-planning optimization

Global Planning		**Description**
Classical Methods	Dynamic Programming	• Systematically evaluates all possible decisions in a multi-step process and obtains all the sub-decisions that minimizes the overall cost. • Capable to acquire the global optimum solution. • Requires full knowledge of the whole system. • Requires great computational efforts • Able to efficiently evaluate the effectiveness of other strategies.
	Linear Programming	• The simplest way to perform optimization that formulated based on linear relationships. • However has rarely been applied in marine applications due to the system complexity.
	Nonlinear Programming	• More commonly adopted in marine applications. • One efficient way to solve the nonlinear problem is by linearization or piecewise linearization. • Quadratic programming is the simplest form and the most commonly used algorithm.
	Mixed integer Programming	• Deals with the optimization problems where some variables are restricted to be integers, such as the number of onboard facilities, switching status, ESS charging and discharging behavior, etc. • Can be incorporated with other linear and nonlinear solvers such as GURROBI, CPLEX, etc.
Heuristic Methods	Genetic Algorithm (GA)	• Based on natural selection and genetic mechanisms. • Capable to deal with complex and nonlinear optimization problems. • Risk of sub-optimal solutions. • Variant: nondominated sorting genetic algorithm II, capable to solve multiobjective problems.
	Particle Swarm Optimization (PSO)	• A stochastic method mimicking the movement and intelligence of swarms. • Fast convergence and good computational efficiency. • Risk of being stuck in local solutions. • Commonly used variant: composite particle swarm optimization.

as an energy buffer that will be charged back to its original energy level at the end, which means that the ESS consumes the same amount of fuel as the generator during charging. The ECMS gives a way of quantitatively converting the electrical power into fuel consumption, which offers an opportunity to evaluate the instantaneous fuel consumption of the system according to the real-time power sharing.

Model Predictive Control

MPC has proven to be an effective and widely used method for real-time optimization. By allowing the system to predict future states and solve the optimization problems at each control time horizon, MPC has proven to be effective, especially in highly dynamic situations. However, it is worth to be noted that while MPC has its own advantages for real-time optimization, better results require a longer prediction horizon and thus result in greater computational efforts. Therefore, the trade-off between the optimality of results and the computing efficiency needs to be carefully addressed when applying MPC in real-time applications.

Distributed Methods

The major difference that distinguishes real-time based PMS from global planning-based PMS is that the former will have to optimize the decisions online with real-time monitored data, and therefore requires faster computational speed and smaller size of the optimization problems. Most of the aforementioned strategies are used to solve centralized optimization problems with the knowledge of whole system information. However, as the future ships develop towards larger scales and more complex structures, the increasing computing efforts put pressure on the centralized algorithms, making distributed power management strategies gaining more interest, as has been discussed in Chapter 1.

Commonly used distributed algorithms in solving shipboard power management problems include Multi-Agent System (MAS) [111–113], Distributed MPC (DMPC) [114–116], Alternating Direction Method of Multipliers [104, 117–119], etc. By dividing the large-scale global optimization problem into several sub-problems, the computational time can be significantly reduced. Currently, the most concerning issues that have been addressed by distributed algorithms include seeking maximum generation support, reducing costs, and demand-side management. However, research in this area is still in its infancy and more fruits are expected in the future.

2.4 Future Trends

Although there has been a significant amount of research work on shipboard power and energy management systems in solving the global or real-time optimization problems, new challenges and requirements have emerged for the future research, and the following aspects are presented to address the future trends:

- Quantitative assessments of management complexity and flexibility are recommended to better evaluate the optimality of the decision and the computational efficiency, especially for real-time applications.
- Considering the increasing penetration of renewable energy resources onboard and the demands of automated operations, robust power and energy management strategies that can maintain high efficiency in the face of uncertainty, communication delays, and forecast failures require further research.
- Power management systems that are in distributed arrangements.
- Human interaction supported power and energy management system is recommended to better monitor and satisfy the onboard customer demands.

3 Conclusion

This paper reviews the state-of-the-art of existing marine PMS/EMS that developed based on optimization algorithms. To start with, it gives a general idea of the most concerned topics and directions of future research by summarizing the optimization objectives and constraints. In addition, existing power and energy management strategies are classified into two categories (i.e., global-planning and real-time), and the commonly adopted approaches in each category are introduced, discussed, and compared. Finally, after a comprehensive review of previous work, future research trends are presented based on current research gaps and the requirements of future marine transportation.

Chapter 3 System Modeling and Optimization Algorithm Development for Hybrid Electrical Ships

Main Contents are as Paper 2:
MPC-informed ECMS based real-time power management strategy for hybrid electric ship

Peilin Xie, Sen Tan, Josep M.Guerrero, Juan C.Vasquez

The paper has been published in
Energy Reports, vol. 7, pp. 126–133, 2021.

Abstract

Risks such as increased mechanical losses, poor power tracking, and low fuel-efficiency power sharing arise due to high fluctuations in propulsion loads caused by the interaction between ship propellers and sea waves. To address these issues, a hybrid-powered SPS is studied where a variable-speed diesel generator (DG) is used as primary power supplier and hybrid energy storage system (HESS) is used for auxiliary. Mathematical model of the system is well established and a MPC-based real-time optimization algorithm is proposed to guide the optimal power allocation among multiple energy sources. The optimization cost function is formulated based on ECMS to minimize the instantaneous fuel consumption according to the real-time load information and generation conditions. Simulations at different sailing speeds validate the fuel-saving ability of the proposed method, and the traditional loss reduction (LR)-based method is used as a benchmark.

1 Summary of the Contribution

- A mathematical model of the hybrid ship is developed, thus laying the foundation for future analysis and strategy design.
- A MPC-based optimization algorithm is proposed that realizes enhanced power tracking performance and improved fuel efficiency while under high propulsion load fluctuations.
- Equivalent consumption minimization strategy is combined with MPC to better adjust its equivalence factor (EF) for more precise prediction performance and enhanced operational fuel efficiency.

2 Main Work

2.1 System Description and Modeling

In order to better deal with the highly fluctuated propulsion loads while maintaining high fuel efficiency, a variable-speed DG is utilized here as the main power supplier and HESS (consisting of battery and ultra-capacitor) is adopted to support the high-frequency loads and provide auxiliary to the DG, as shown in Fig. 3.1.

Variable-speed Diesel Generator

The major difference between a variable-speed DG and a traditional fixed-speed DG is that the former allows the engine speed to vary within a specific

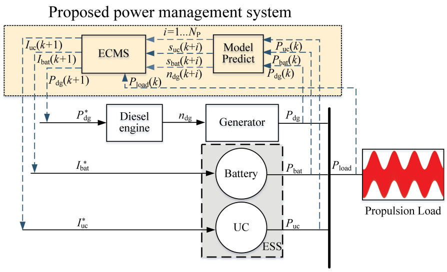


Fig. 3.1: Overview of the studied SPS and the PMS scheme

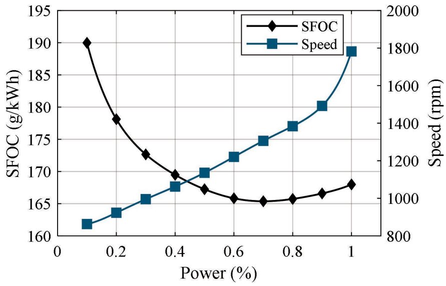


Fig. 3.2: SFOC and engine speed versus output power

range. In doing so, fuel efficiency can be improved by 10% to 20% [120]. Fig. 3.2 gives the curves of specific fuel oil consumption (SFOC) and the corresponding engine rotational speed under certain power conditions for the variable-speed DG. And the relationships between them can be expressed as the following nonlinear functions,

$$P_{eng} = a_0 + a_1 n_{dg} + a_2 n_{dg}^2 + a_3 n_{dg}^3 \tag{3.1}$$

$$SFOC = \begin{cases} b_0 + b_1 n_{dg} + b_2 n_{dg}^2 + b_3 n_{dg}^3 & \\ +b_4 n_{dg}^4 + b_5 n_{dg}^5 + b_6 n_{dg}^6 & n_{dg} <= 1340 \\ c_0 + c_1 n_{dg} + c_2 n_{dg}^2 & n_{dg} > 1340 \end{cases} \tag{3.2}$$

where a_0, a_1, a_2, a_3 and $b_0, b_1, b_2, b_3, b_4, b_5, b_6$ are constant values calculated by curve fitting respectively. P_{eng} is the engine output power and n_{dg} denotes the rotational speed.

Considering the electrical power losses ($P_{loss_{dg}}$), the terminal power of DG (P_{dg}) can be calculated by,

$$P_{dg} = P_{eng} - P_{loss_{dg}} \tag{3.3}$$

$$P_{loss_{dg}} = k_c T^2 + k_i \omega + T_f \omega + k_w \omega^3 + C \tag{3.4}$$

where k_c, k_i, T_f, k_w, C are the coefficients that represent copper loss, iron loss, friction loss, windage loss, and constant loss respectively.

Hybrid Energy Storage System

To better support the highly fluctuated load and ensuring that the variable-speed DG operates at high fuel-efficiency points, a hybrid energy storage system that consists of ultra-capacitors (UCs) and batteries, is utilized here. The simplified mathematical model of the HESS is represented as:

$$\begin{bmatrix} \dot{s_b} \\ \dot{s_{uc}} \end{bmatrix} = \begin{bmatrix} 1/(3600Q_b) & 0 \\ 0 & -1/(V_{uc}C_{uc}) \end{bmatrix} \begin{bmatrix} I_b \\ I_{uc} \end{bmatrix} \tag{3.5}$$

where s_b, s_{uc} are the SOC of battery and UC, respectively. Q_b is the battery capacity, V_{uc} represents the maximum UC voltage, C_{uc} is the UC capacitance, and I_b, I_{uc} are the currents of the battery and UC respectively.

And the terminal output power of battery (P_b) and UC (P_{uc}) can be expressed as,

$$P_b = V_{oc}I_b - P_{loss_b} = V_{oc}I_b - R_bI_b^2 \tag{3.6}$$

$$P_{uc} = V_{uc}s_{uc}I_{uc} - P_{loss_{uc}} = V_{uc}s_{uc}I_{uc} - R_{uc}I_{uc}^2 \tag{3.7}$$

where V_{oc} is the battery open-circuit voltage, R_b and R_{uc} are the internal resistance, and P_{loss_b} and $P_{loss_{uc}}$ are the electrical power losses.

Propeller and Ship Hydrodynamics

As has been discussed in Chapter 1, propulsion load fluctuates due to the interaction between propellers and sea waves. The in-and-out-of-water behavior of propellers is the main cause of high-frequency fluctuations, which can reach 10 Hz. And the periodical wave is the major cause of low-frequency fluctuations and is considered as 0.1 Hz in this paper.

2.2 Optimization Problem Formulation

In order to maintain high operational efficiency under high load fluctuations, it is essential to have an optimal power splitting between multiple energy sources (DG, UCs, and batteries in this case). Therefore, an optimization process is developed as shown in Fig. 3.1.

The cost function is formulated based on ECMS, which gives a way to calculate the equivalent fuel consumption of batteries (m_b) and UCs (m_{uc}) as introduced in Chapter 1. Afterwards, the overall system fuel consumption (m_{total}) is obtained after summing the equivalent fuel consumption from HESS with the real fuel consumption from DG (m_{dg}):

$$m_{total} = m_{dg} + m_b + m_{uc} \tag{3.8}$$

where m_{dg} is calculated based on the instantaneous output power P_{dg}, the SFOC value, and the efficiency η_{dg}, as shown below,

$$m_{dg} = SFOC \cdot P_{dg}/(\eta_{dg} \cdot 3.6 \cdot 10^6) \tag{3.9}$$

And m_b, m_{uc} are expressed as,

$$m_b = ef_b \cdot SFOC_{eq} \cdot P_b/(3.6 \cdot 10^6) \tag{3.10}$$

$$m_{uc} = ef_{uc} \cdot SFOC_{eq} \cdot P_{uc} / (3.6 \cdot 10^6) \tag{3.11}$$

where $SFOC_{eq}$ is the equivalent SFOC of HESS, set equal to the peak value of DG SFOC considering the additional energy losses during charging and discharging behaviors. In this way, DG is encouraged to take on more load, thus is allowed to work at high load conditions with high fuel efficiency.

ef_b and ef_{uc} represent the EFs of battery and UC respectively, standing for the conversion from the electrical power to fuel consumption. In most previous studies, EFs are set as constants to simplify the calculation process, however, the accuracy is sacrificed. Here in this paper, the EF is allowed to be adjusted in real-time to achieve more accurate equivalent fuel conversion results. The calculation of ef_b and ef_{uc} follows the following equations,

$$ef_b = \begin{cases} \dfrac{k_b}{\eta_{dg} \cdot \eta_{dis} \cdot \eta_{chg.av}} & P_b \geq 0 \\ \dfrac{k_b \cdot \eta_{chg} \cdot \eta_{dis.av}}{\eta_{dg}} & P_b < 0 \end{cases} \tag{3.12}$$

where η_{chg} and η_{dis} refer to the battery charging and discharging efficiency, and $\eta_{chg.av}, \eta_{dis.av}$ are their average values. k_b stands for the battery penalty coefficient, which varies according to the instantaneous SOC level, and is calculated as,

$$k_b = 1 - \mu_b \frac{s_b - (s_{b.min} + s_{b.max})/2}{(s_{b.min} + s_{b.max})/2} \tag{3.13}$$

where $s_{b.min}, s_{b.max}$ gives the upper and lower SOC limits. μ_b is a constant coefficient to penalize the deviations of s_b from the middle value. In this way, batteries are encouraged to discharge under high SOC conditions and charge under low SOC conditions, ensuring a healthy energy backup.

Similar equations hold for the calculation of ef_{uc}. For details please refer to Paper 2.

Given the amount of system equivalent fuel consumption, model predictive control is integrated into the optimization process to estimate and predict the SOC conditions, calculate the future step's EFs, and solve the optimization problem during each sampling step. And the reformulated cost function and the constraints are given as follows,

$$\begin{aligned} \min \quad & J = \textstyle\sum_{j=k}^{k+N_p-1} m_{total}(t_j) \\ s.t. \quad & P_{dg}(t_j) + P_b(t_j) + P_{uc}(t_j) = P_{load} \\ & n_{dg}(t_j) \in [n_{dg.min}, n_{dg.max}] \\ & I_{b/uc}(t_j) \in [I_{b/uc.min}, I_{b/uc.max}] \\ & s_{b/uc}(t_j) \in [s_{b/uc.min}, s_{b/uc.max}] \\ & \Delta n_{dg} \leq \Delta n_{dg.max} \\ & \Delta I_{b/uc} \leq \Delta I_{b/uc.max} \\ & \Delta s_{b/uc} \leq \Delta s_{b/uc.max} \end{aligned} \tag{3.14}$$

where N_p is the prediction horizon of MPC. The equal constraint guarantees the system power balance, and the inequality constraints limit the electrical and mechanical operational boundaries of DG and HESS.

2.3 Simulation Results

To verify the effectiveness of the proposed power management strategy, simulations are conducted for a hybrid-powered DC ship. Parameters of the onboard facilities are given in Tab. 3.1. Traditional LR-based strategy is used as a benchmark.

Table 3.1: Parameters of onboard facilities

Facility	Quantity	Parameters	Values
Diesel Generator	1	Rated power P_d^*	2 MW
		Efficiency η_d	96%
Battery	10	Rated power P_b^*	25.6 kW
		Capacity Q	100 Ah
		Resistance R_{bat}	64 mΩ
		SOC Range $s_{b.min/max}$	0.2, 0.9
		Initial SOC $s_{b.init}$	0.5
Ultra-capacitor	10	Rated power P_{uc}^*	25 kW
		Capacitance C_{uc}	63 F
		Resistance R_{uc}	8.6 mΩ
		SOC Range $s_{uc.min/max}$	0, 1
		Initial SOC $s_{uc.init}$	0.5

Vessel Operational Test

Fig. 3.3 and Fig. 3.4 show the ship performance during accelerating and fixed-speed cruising, respectively. In Fig. 3.3, ship accelerate from 0 to 7 knots. It is clear that the high-frequency fluctuations are supported by the UCs, while batteries and DG share the low-frequency load demand. In addition, in order to be more fuel-efficient, DG is maintained at high loading conditions. As seen, batteries are charged to avoid DG low-load operation in the beginning and are discharged back after 190 s when the load demand is high. Fig. 3.4 gives the performance comparison between the proposed method and the traditional LR-based method. The two methods show similar performance in power tracking, however, the proposed method ensures higher loading of DG and higher SOC level of HESS, which means more sufficient energy backup and higher fuel efficiency. Detailed comparisons in terms of fuel savings are given below.

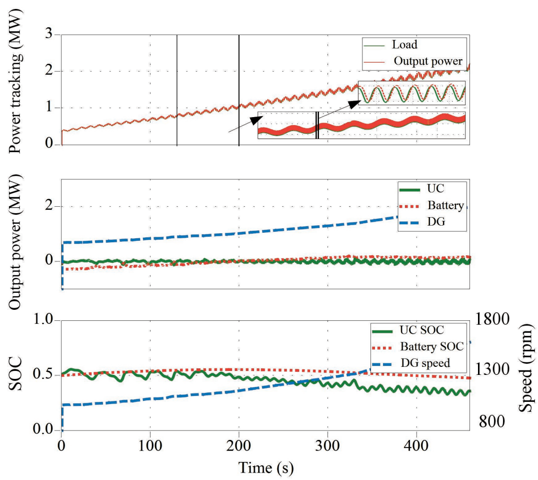
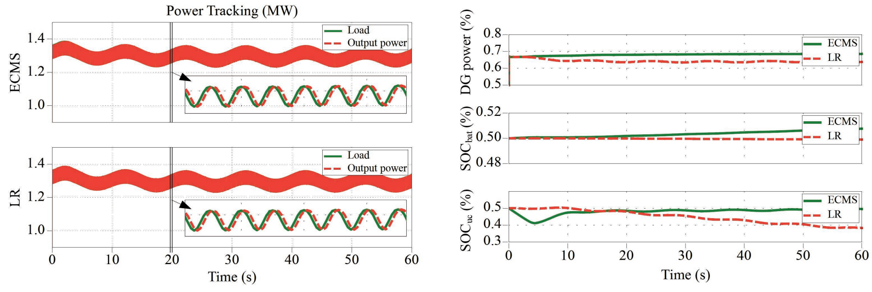


Fig. 3.3: Performance during ship accelerating

Fuel Saving Comparison

Tab. 3.2 presents the results of overall fuel consumption and final battery SOC for 15-minute fixed-speed cruises. Concluded from the table, the utilization of variable-speed DG achieves up to 4.3% energy savings compared to fixed-speed DG, and by the end of the voyage, more energy is stored in ESS when adopting the proposed ECMS-based strategy. Therefore, the conclusion can be drawn that the proposed method consumes less fuel while maintaining a higher SOC level.



(a) Power tracking performance (b) Output power and HESS SOC

Fig. 3.4: Performance during ship fixed-speed sailing

Table 3.2: Comparison results

PMS algorithm	DG type	Vessel speed			
		3 knots	5 knots	5.5 knots	6.2 knots
		Consumed fuel (kg)			
ECMS	Fix speed	27.08	55.89	64.04	83.43
	Variable speed	26.67	54.81	62.73	79.88
LR	Fix speed	27.23	56.20	64.26	83.52
	Variable speed	26.72	55.17	62.78	80.37
		Final battery SOC			
ECMS	Variable speed	0.5855	0.5045	0.5405	0.5270
LR	Variable speed	0.4865	0.4910	0.4820	0.4955

3 Conclusion

In order to better deal with the propulsion load fluctuations, this paper recommends the hybrid use of ultracapacitors and batteries as auxiliary and high fuel-efficiency variable-speed diesel generators as the main power supplier. And to capture the characteristics of the onboard facilities, the simplified mathematical model are established that largely reduce the computing efforts. In addition, to determine the optimal power distribution among them, a real-time PMS is developed. The proposed predictive optimization algorithm is able to estimate and adjust the equivalence factor according to the instantaneous system states, thus ensuring the most fuel-efficient power allocation. Simulation results also validate that the proposed PMS is effective in ensuring energy reservation and reducing fuel consumption.

However, although the proposed optimization strategy gives a solution for real-time optimal power distribution, one major concern and drawback of the current study is that it lacks a long-term perspective and is therefore unsure to be robust in facing changes in cruising states or external environmental factors. Considering that the propulsion loads would vary largely under different sailing conditions and sea states, guaranteeing a healthy energy backup as well as fuel-efficient operation throughout the whole voyage is essential. The content in this Chapter lays the foundation for the development of a more functional and robust PMS, which brings the research of next Chapter.

Chapter 4 Centralized Multi-layer PMS Designing for Hybrid Electrical Ships

Main Contents are as Paper 3: A Real-time Power Management Strategy for Hybrid Electrical Ships under Highly Fluctuated Propulsion Loads

Peilin Xie, Sen Tan, Najmeh Bazmohammadi, Josep M. Guerrero, Juan C. Vasquez

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IEEE Systems Journal in June, 2022.

Abstract

Due to different sea states, variable shipping conditions, and changeable vessel speeds, propulsion loads could be highly fluctuating and hard to predict in ahead of time. And the presence of highly fluctuating propulsive loads puts additional pressure on system stability, operational efficiency and continuity of power supply. In order to guarantee a high fuel efficiency operation while maintaining sufficient energy backup even under extreme sea conditions, a real-time two-layer PMS scheme is proposed to provide optimal power splitting decisions. In addition, a multi-step load forecasting (MSLF) system is developed and integrated to provide accurate future load information. To validate the effectiveness of the proposed PMS, multiple case studies are conducted taking into account different sea states, shipping conditions, sailing time, cruising speed, and propeller submergence ratios. In addition, the robustness of the proposed method is also demonstrated by sensitivity analysis in terms of initial battery SOC and charging/discharging efficiency.

1 Summary of the Contribution

- A two-layer PMS scheme is proposed to schedule the on/off of DG and the optimal power allocation between DG and HESS with consideration of energy reservation and fuel-efficiency operation.
- A real-time MSLF system is developed that predicts the near future load information to improve power tracking ability and provide MPC with opportunities for wiser decisions.

2 Main Work

To cope with frequent load fluctuations and maintain high fuel efficiency, a hybrid SPS consisting of a variable speed DG and a HESS is investigated with a structure similar to the one discussed in Chapter 3. Furthermore, in order to achieve high fuel-efficiency operation while maintaining a healthy SOC level of HESS throughout the voyage, a two-layer PMS scheme is proposed in which a novel MSLF system is integrated, as shown in Fig. 4.1.

2.1 Two-layer PMS Scheme Construction

As seen, the outer layer is rule-based, guiding the on/off of DG based on the instantaneous SOC of HESS and load demand, while the inner layer is optimization-based, solving the optimization problem in real-time with the future load information predicted by the MSLF system.

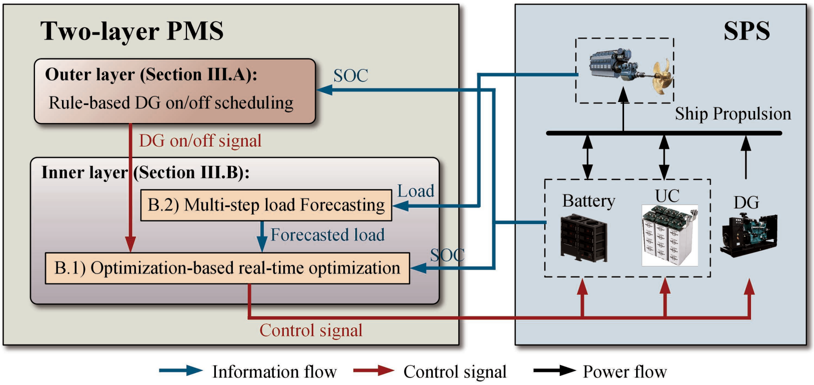


Fig. 4.1: Proposed two-layer PMS scheme

Outer Layer

The basic idea of the outer layer is to avoid overcharging and over-discharging the batteries while preventing the DG from low-load operations. To do that, the on/off status of DG is decided by the following rules as Fig. 4.2.

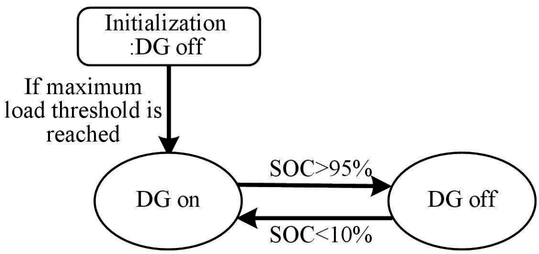


Fig. 4.2: Outer layer

Once the outer layer gets the on/off signal of DG, it then sends the signal to the inner layer, where the optimal power splitting decisions are made.

Inner Layer

As shown in Fig. 4.1, the inner layer consists of two parts: the MSLF system and the optimization system. MSLF predicts the near-future load with historical load information and the optimization system optimizes the power distribution between multiple energy resources with the information from MSLF and the outer layer. The detailed control scheme is shown in Fig. 4.3.

The optimization system is built based on MPC, similar to the algorithm developed in Chapter 3, except that Eq. (3.14) is modified as Eq. (4.1). The only difference between them is that instead of repeatably using the

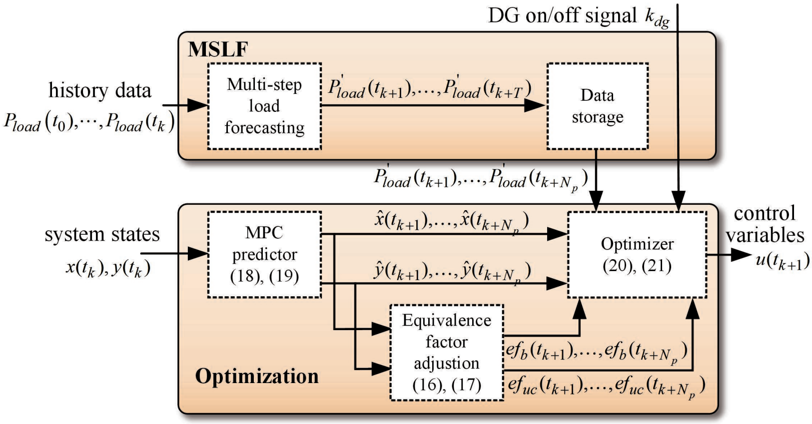


Fig. 4.3: Inner layer

same load (P_{load}) value during one prediction horizon, the load information ($P'_{load}(t_j)$) is updated by MSLF at each step to obtain more informed decisions.

$$\begin{aligned}
\min_{u(t_j)} \quad & J = \textstyle\sum_{j=k}^{k+N_p-1} m_{total}(t_j) \\
s.t. \quad & P_{dg}(t_j) + P_b(t_j) + P_{uc}(t_j) = P'_{load}(t_j) \\
& n_{dg}(t_j) \in [n_{dg.min}, n_{dg.max}] \\
& I_{b/uc}(t_j) \in [I_{b/uc.min}, I_{b/uc.max}] \\
& s_{b/uc}(t_j) \in [s_{b/uc.min}, s_{b/uc.max}] \\
& \Delta n_{dg} \leq \Delta n_{dg.max} \\
& \Delta I_{b/uc} \leq \Delta I_{b/uc.max} \\
& \Delta s_{b/uc} \leq \Delta s_{b/uc.max}
\end{aligned} \tag{4.1}$$

To obtain the future several steps' load (P'_{load}), a MSLF system is developed based on the auto-regressive integrated moving average (ARIMA) model. The overall structure of the MSLF is shown in Fig. 4.4.

After gathering the load information from the past several minutes, the MSLF builds the corresponding ARIMA model and predicts the future T steps all at once ($T > N_p$). Since the MPC prediction horizon is set to N_p, MSLF sends the predicted values to the optimization system sequentially in the order of N_p per sampling time. And the prediction process is reactivated until all T predictions are run out.

One of the major benefits of the proposed MSLF is that it has the capability of multi-step prediction with relatively high accuracy while not requiring long-term data training time, which makes it more suitable for highly dynamic conditions and real-time applications. To validate it, comparisons between the traditional used linear prediction (LP) method and the proposed

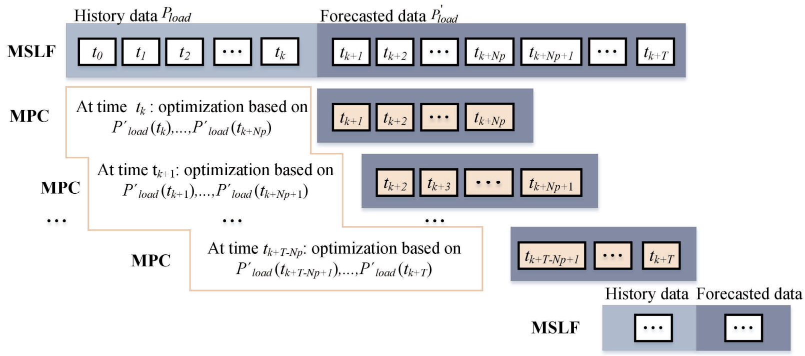
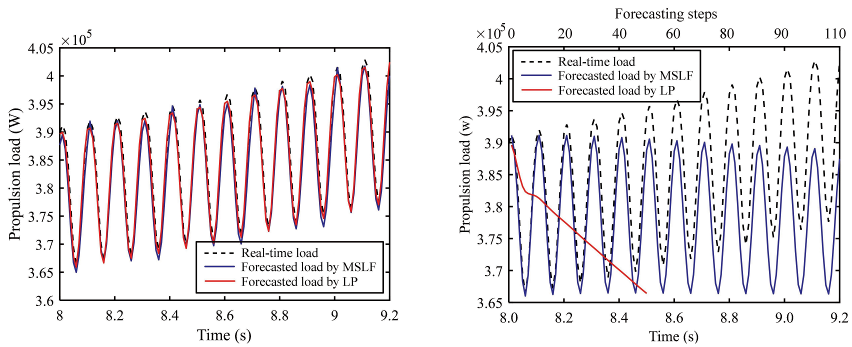


Fig. 4.4: Overall structure of MSLF



(a) One-step prediction (b) Multi-step prediction

Fig. 4.5: Forecasting performance comparision

MSLF are conducted and the results are shown in Fig. 4.5. As seen, compared to LP, the proposed MSLF acquires a similarly good performance in one-step prediction, but much better performance in multi-step predictions.

To test the feasibility of the proposed optimization algorithm and the load forecasting system in terms of real-time applications, the computing time of them are statistically calculated and the results are shown in Fig. 4.6. The sampling time for the optimization is set to 0.01 s while for the MSLF is 0.3 s. As seen, both processes manage to complete the computations within their sampling time, which proves their feasibility in real-time applications.

2.2 Simulation Results

In order to evaluate the effectiveness of the proposed PMS, multiple case studies are conducted including different sea state tests and different cruising

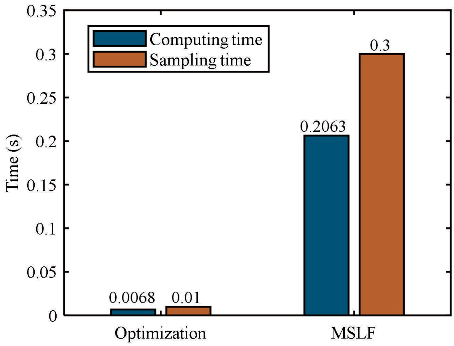


Fig. 4.6: Computing time

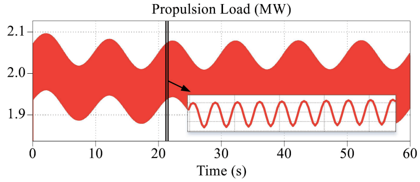
condition tests.

Different Sea State Tests

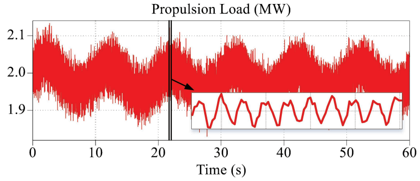
According to the ship hydrodynamic model as in Chapter 1, the behavior of propeller in and out of water is the major cause of the propulsion load fluctuation. And it is usually expressed using the propeller submergence ratio h/D. Changes in h/D would have a direct impact on the propulsion load. In most previous work, h/D is simply modeled as an ideal sine wave (Fig. 4.7(a)), however not be accurate in practice. Due to the presence of small ripples, trembles, or disturbances from nature, the noises exist as shown in Fig. 4.7(b). In addition, for ships under a high propeller submergence ratio, the propulsion load would show characteristics of the flat-topped sine wave as in Fig. 4.7(c). Fig. 4.8 shows the performance of power tracking and load forecasting under the three load conditions. All three cases show good prediction accuracy and less power tracking delay with MSLF integrated, which proves the effectiveness of the proposed MSLF system and proposed PMS as well.

Cruising Condition Tests

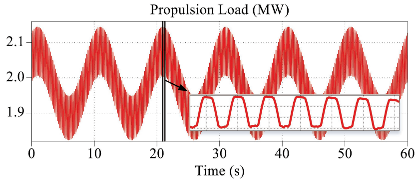
Considering the effects of shipping states on the propulsion loads, here a one-hour cruise is studied including different cruising modes: acceleration, high-speed sailing, deceleration, and occasionally speed changes as shown in Fig. 4.9. It can be observed that UCs support the high-frequency fluctuating load, while DG and batteries share the low-frequency loads. In addition, the DG is maintained at high load conditions throughout the whole voyage with the assistance of the batteries and the outer-layer PMS.



(a) Ideal load

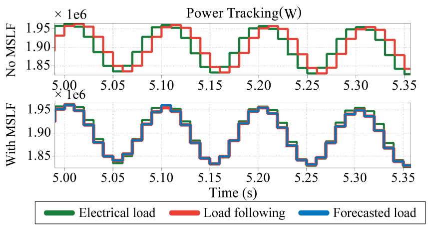


(b) Load with noises

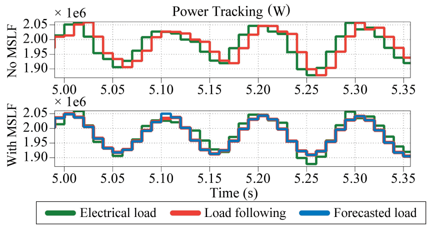


(c) Load under high submergence ratio

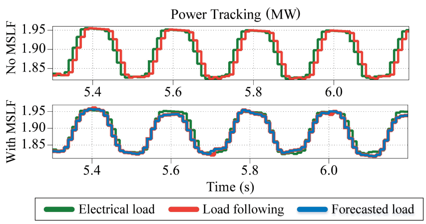
Fig. 4.7: Propulsion load fluctuations under three cases



(a) Ideal load



(b) Load with noises



(c) Load under high submergence ratio

Fig. 4.8: Power tracking and load forecasting performance

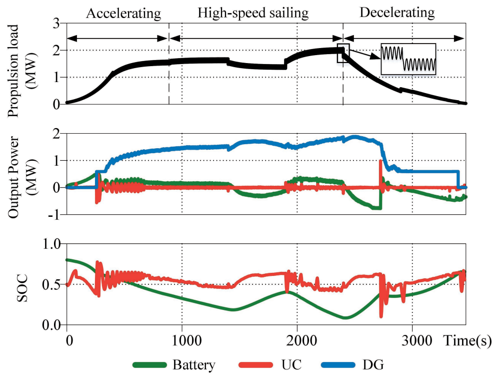


Fig. 4.9: Performance under one-hour cruising

Table 4.1: Fuel consumption and final HESS SOC

Method	Fuel consumption (kg)	Final s_{uc}	Final s_b
Proposed	206.6	0.9	0.9
LR-based	212.1	0.85	0.2

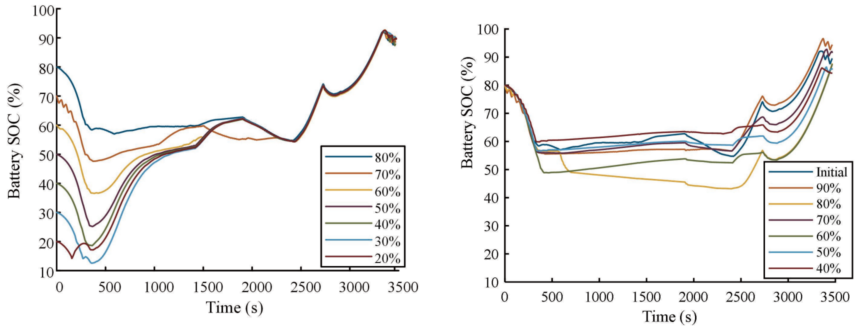
For the purpose of evaluating the fuel saving capability of the proposed PMS, a comparison was made with the conventional LR-based approach. Results are shown in Tab. 4.1, not only HESS maintains a higher SOC level, but also obtains 2.6% improvement in fuel savings.

To be concluded, the developed MSLF shows good accuracy in both ideal and complex sea conditions and helps to reduce power tracking delays caused by sampling. In addition, by applying the proposed PMS, DG is maintained at high fuel-efficiency operational points and a healthy SOC level of HESS can be guaranteed throughout different cruising states.

2.3 Sensitivity Analysis

Considering that the above work is based on the assumption that all initial states of batteries are 50% and that their internal parameters are known, sensitivity analysis is necessary in evaluating the effectiveness and robustness of the proposed PMS under different initials or unknown situations. Therefore, simulations are conducted under different initial SOC states and charging/discharging efficiencies. Results are shown in Fig. 4.10(a) and Fig. 4.10(b) respectively, and the fuel consumption under each circumstances is presented in Tab. 4.2 and Tab. 4.3.

Results show that batteries manage to be maintained at a relatively high SOC level at the end of the voyage, even starting from extremely low initial values. However, low initial SOC levels and decreases in battery efficiency



(a) Initial battery SOC (b) Battery charging/discharging efficiency

Fig. 4.10: Sensitivity analysis

Table 4.2: Fuel consumption under different initial battery SOC

Initial SOC (%)	80	70	60	50	40	30	20
Fuel consumption (kg)	2.052	2.085	2.095	2.115	2.14	2.161	2.217

Table 4.3: Fuel consumption under different $\eta_{chg,dis}$

$\eta_{chg,dis}$ (%)	initial	90	80	70	60	50	40
Fuel consumption (kg)	2.052	2.054	2.059	2.062	2.073	2.085	2.087

would lead to an increase in energy consumption.

3 Conclusion

In order to maintain ship normal operation with improved fuel economy under high load fluctuations, a real-time two-layer PMS is developed. The proposed PMS schedules the complex power flowing among different types of energy sources in a high fuel-efficiency way. To better handle the high dynamic load situation, a real-time MSLF system is developed that has the advantages of multi-step forecasting, high accuracy, and short processing time. Comprehensive case studies are conducted under different sea states and cruising conditions to fully test the effectiveness of the proposed PMS.

Chapter 5 Distributed PMS Designing for ZED-based Ships

Main Contents are as Paper 4: A distributed real-time power management scheme for shipboard zonal multi-microgrid system

Peilin Xie, Sen Tan, Najmeh Bazmohammadi, Josep M.Guerrero, Juan C.Vasquez, Jose Matas Alcala, Jorge El Mariachet Carreño

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Applied Energy, vol. 317, 2022.

Abstract

Although there has been plenty of research work on shipboard power management systems, most of them are developed based on centralized arrangements that enable global optimum solutions but consume many computational efforts and suffer from single-point failures. Considering the future trend of the shipping industry towards large scales and zonal distribution, traditional centralized PMS would be inappropriate for practical applications due to the complex electrical systems, multiple types of energy resources, and increasing amount of processing data. Therefore, a real-time distributed PMS is developed here for zonal multi-microgrid ships to achieve safe, efficient, and resilient operation under frequent load fluctuations. The proposed PMS is in simple structure and fast in computation and convergence. Multiple case studies validate the efficiency of the presented PMS with regard to fuel savings, energy reservations, and robustness against faulty conditions.

1 Summary of the Contribution

- A distributed PMS scheme is proposed that achieves the optimal power distribution among multiple energy sources and electrical zones. High fuel efficiency operation and healthy SOC of the battery can be guaranteed throughout the whole voyage.
- The proposed PMS manages the real-time power splitting problems through three layers, thus improving the computational efficiency. Moreover, the distributed scheme allows the global optimization problem to be solved by each zone, which further reduces the computing effort. In addition, the developed distributed algorithm is fast in convergence and computation. All these make the developed PMS consume less computational resources and thus suitable for real-time applications.
- By allowing zonal communication and transmission, neighboring zones can support each other, thereby enhancing system resilience against faulty conditions.

2 Main Work

2.1 System Description

As shown in Fig. 5.1, the studied shipboard power system is divided into four zones, each managed by a local PMS controller. All four zones have a similar composition of energy sources but different types of local loads. Due to physical limitations, the primary loads in Zone 1 and Zone 4 are propulsion loads. And the primary loads for Zone 2 and Zone 3 are ship service loads. The local zonal PMS controller communicates only with adjacent zones to determine the optimal intra-zone power distribution and inter-zone power transmission.

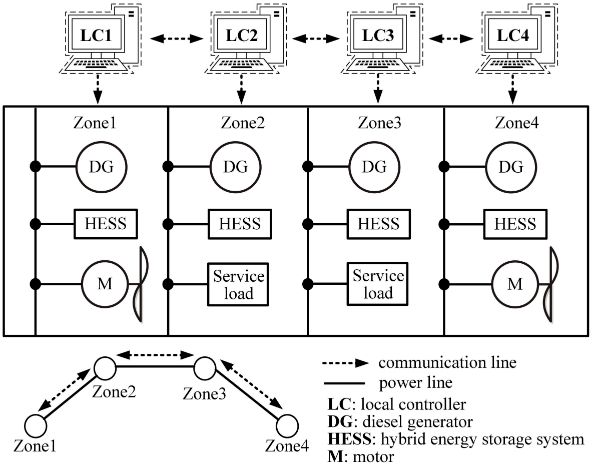


Fig. 5.1: Overall system structure

2.2 Distributed PMS Development

To address the problem of optimal power allocation under high propulsion load fluctuations, a distributed three-layer PMS scheme is developed. Each zone shares similar PMS structure as shown in Fig. 5.2.

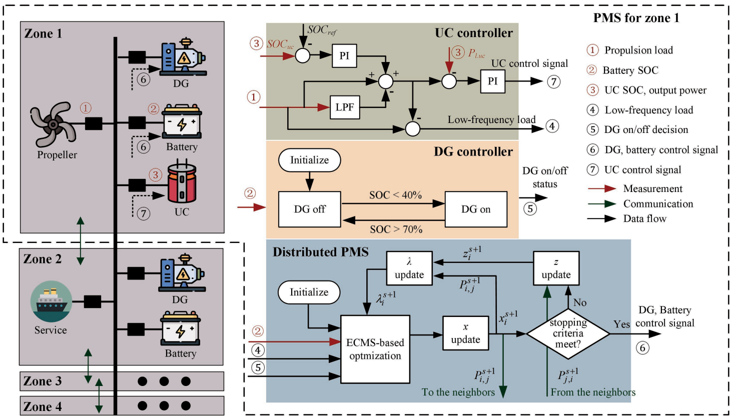


Fig. 5.2: Local PMS for Zone 1

As seen, the proposed PMS consists of filter-based UC controller, rule-based DG on/off controller, and the optimization-based layer. Through the three parts, loads are efficiently distributed among the multiple energy sources.

UC Controller

To support the highly fluctuating propulsion load with much more efficiency and less computational efforts, filter-based UC controller is developed that filters the loads into high-frequency part and low-frequency part. The high frequency loads are supported by UCs. In addition, in order to prevent the UC from over-charging or over-discharging, a PI controller is adopted, as can be seen in Fig. 5.2. Afterward, low-frequency load information is sent to the lower layers.

DG Controller

The DG controller decides the DG on/off state according to the local HESS SOC conditions. The basic idea is to ensure that DG works at high efficiency point and the battery at healthy SOC levels. The rule-based algorithms is similar as described in Chapter 4. And the DG on/off signal is also sent to the optimization controller, where optimal power splitting decisions are made.

Optimization Controller

The optimization controller gathers local information of local loads, DG status, and the neighboring information to optimize the power splitting with highest fuel efficiency. The cost function is formulated based on ECMS, similar to the content discussed in Chapter 3 and Chapter 4, except that it is coupled with the neighbors:

$$
\begin{aligned}
\min_{u_i(t_k)} \quad & J = \sum_{i=1}^{N} m_{i,total}(u_i(t_k)) \\
& P_{i,dg}(t_k) + P_{i,b}(t_k) = P_{i,lowfreq}(t_k) + \sum_{j\in\mathbb{N}_i} P_{i,j}(t_k) \\
& P_{i,j}(t_k) + P_{j,i}(t_k) = 0, \forall j \in \mathbb{N}_i \\
& n_{i,dg}(t_k) \in [n_{dg.min}, n_{dg.max}] \\
& I_{i,b}(t_k) \in [I_{b.min}, I_{b.max}] \\
& SOC_{i,b}(t_k) \in [SOC_{b.min}, SOC_{b.max}] \\
& P_{i,j}(t_k) \in [P_{i,j.min}, P_{i,j.max}] \\
& \Delta n_{i,dg} \le \Delta n_{dg.max} \\
& \Delta I_{i,b} \le \Delta I_{b.max}
\end{aligned}
\tag{5.1}
$$

where i denotes the series number of Zone i, u is the control vector and includes the rotational speed of DG (n_{dg}) and the current of battery (I_b). N is the total amount of zones, and in this case, is considered as 4. $\mathbb{N}_i$ represents all the neighbors of zone i. $P_{i,lowfreq}$ is the low-frequency load. $P_{i,j}$ denotes the power transmitted from zone i to zone j.

As seen from Eq. (5.1), the only coupling exists in the power balance constraint and is caused by the power transmission between the adjacent zones. To decouple it, for Zone i, we define two new variables $z_{i,j}$ and $z_{mid,ij}$ which represents the local copy of $P_{j,i}$ and the middle agreement on the transmission power, respectively, as presented in the following equations:

$$z^s_{i,j} - P^s_{j,i} = 0, \forall j \in \mathbb{N}_i \tag{5.2}$$

$$z^s_{mid,ij} = \frac{1}{2}(P^s_{i,j} - z^s_{i,j}) \tag{5.3}$$

In order to gain the optimization results in an efficient way, a distributed algorithm is developed based on the alternating direction method of multipliers (ADMM), and the procedure is shown in Fig. 5.3.

Convergence tests are conducted and the results are shown in Fig. 5.4. It can be seen that 74.6% of the cases converge after one iteration, and most of them converge within five iterations, thus showing a fast convergence speed.

2.3 Case Studies

In order to validate the effectiveness of the proposed PMS in terms of operational efficiency and resilience, two scenarios are studied including normal and faulty conditions.

Normal Conditions

Fig. 5.5 shows the load profile for a one-hour cruise, including ship acceleration, high-speed sailing, and deceleration. The green curve represents the ship propulsion load, which is highly periodic and fluctuating due to the propeller in-and-out-of-water effects. While the red curve shows the profile of the ship service loads and is represented by a series of step changes.

Simulation results including the power tracking performance, power splitting, and SOC conditions of each zone are given in Fig. 5.6. The following comments can be drawn based on the analysis of the results:

- Good power tracking performance is maintained in all four zones.
- The HESS SOC remains healthy throughout the voyage.
- The primary load is provided by DG and batteries, and the high-frequency components are supported by UCs.

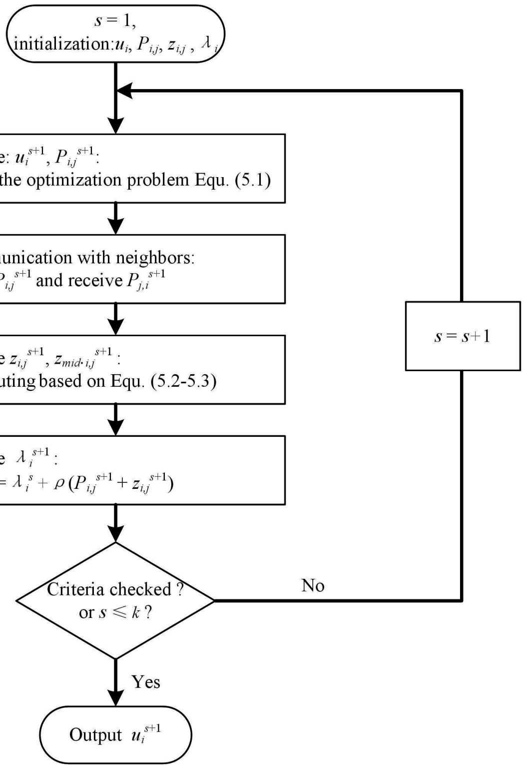
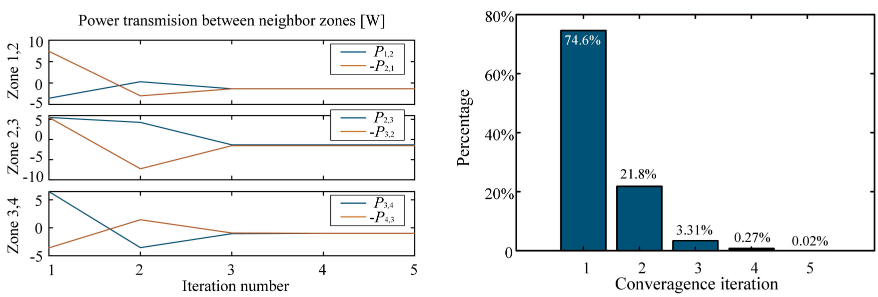


Fig. 5.3: The procedure of distributed optimization solving algorithm



(a) Convergence performance over one sampling instance

(b) Convergence rate over 70000 samples

Fig. 5.4: Convergence tests

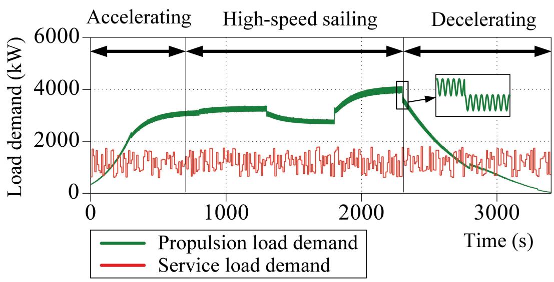


Fig. 5.5: Load profile

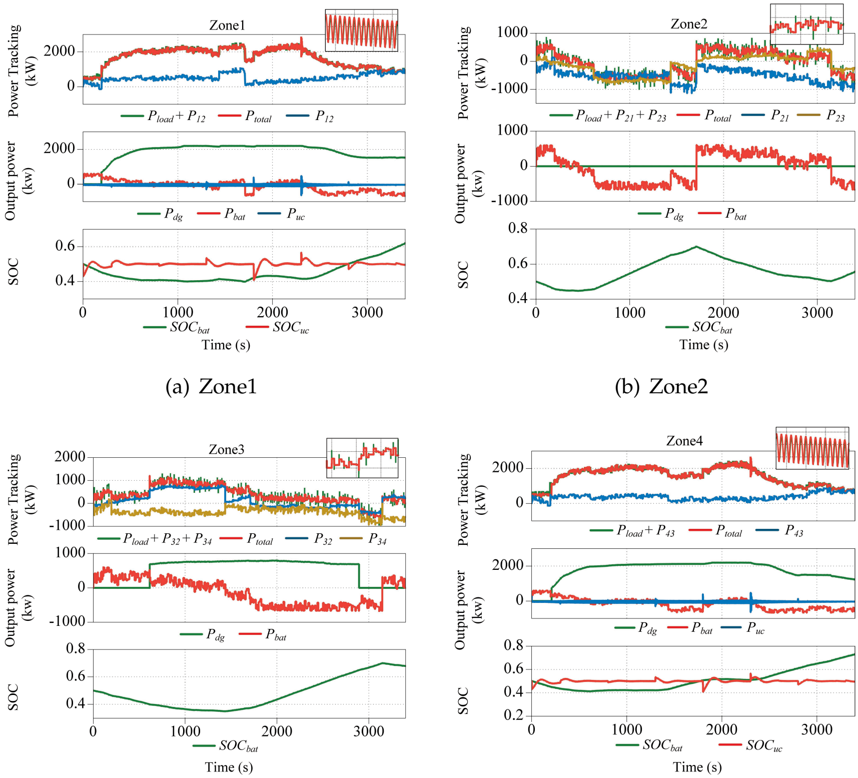
- DGs are turned on during high load conditions and turned off during low load conditions. Meanwhile, battery charge and discharge states are adjusted to maintain DG high-load operations.
- Power exchange exists between adjacent zones, which allows the high power zones to support low power zones.

In addition, in order to better evaluate the fuel saving ability and the calculating efficiency of the proposed PMS, comparisons are made with the conventional centralized PMS and the decentralized PMS. Results can be found in Tab. 5.1. It can be concluded that the centralized PMS achieves the lowest fuel consumption however requires the longest computational time of all. While the proposed distributed PMS shows almost similar fuel consumption as the centralized one but reduces the computation time by 28%. Although the decentralized PMS has the fastest computational speed, it requires 5.3% more fuel and lacks the ability of zonal support.

In conclusion, the case study under normal operational conditions demonstrates that the proposed PMS achieves good power tracking performance, healthy SOC level, high fuel efficiency, and fast computing speed under high fluctuating loads and variable operating states.

Table 5.1: Fuel consumption and computing time of the proposed distributed, centralized, and decentralized PMS

PMS arrangement	Final battery SOC				Consumed	Computing
	Zone1	Zone2	Zone3	Zone4	fuel (kg)	time (ms)
Distributed	0.573	0.525	0.551	0.540	637.1	5
Centralized	0.6	0.542	0.542	0.6	632.4	6.9
Decentralized	0.53	0.57	0.57	0.53	672.6	4



(a) Zone1 (b) Zone2

(c) Zone3 (d) Zone4

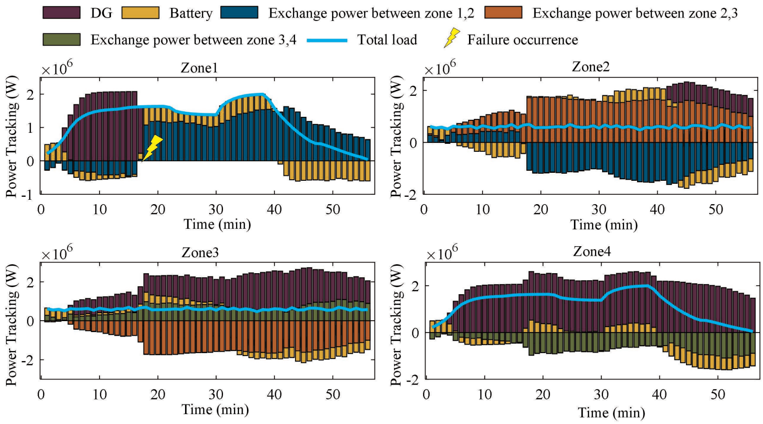
Fig. 5.6: Zonal performance

Faulty Conditions

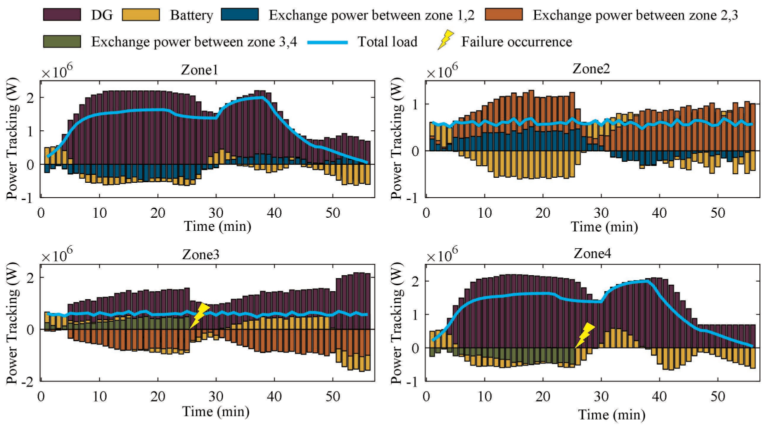
In order to test the system resilience against faulty conditions, two types of failures are tested here including DG failure and zonal disconnection. Results of system power-sharing and SOC conditions are shown in Fig. 5.7 and Fig. 5.8, respectively.

For the case of DG failure, DG in Zone 1 suddenly fails at $t = 1000s$, as we can see a huge drop of DG output power in Zone 1 in Fig. 5.7(a). After the failure occurs, the remaining zones start to support Zone 1, which guarantees the continuity of power supply and the stability of the entire system. In addition, the batteries in all four zones remain at healthy SOC levels and are recharged to high SOC conditions at the end of the cruise, which not only prevents the DG from the low-load operation but also ensures continues power supply by maintaining healthy HESS SOC levels.

And for the second case, Zone 3 and Zone 4 electrically disconnect at

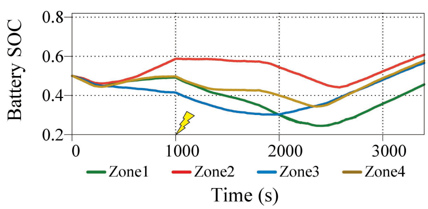


(a) DG sudden faulure in Zone 1

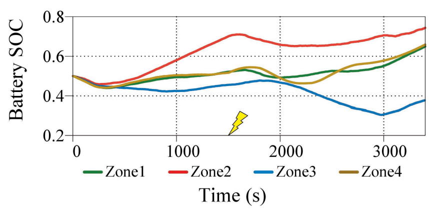


(b) Sudden disconnection between Zone 3 and Zone 4

Fig. 5.7: Load sharing under faulty conditions



(a) DG sudden faulure in Zone 1



(b) Sudden disconnection between Zone 3 and Zone 4

Fig. 5.8: Battery SOC under faulty conditions

time 1500s, at which point it can be observed a sudden drop of exchanging power between Zone 3 and Zone 4 in Fig. 5.7(b). Before the disconnection occurs, Zone 4 is supporting its neighbors by generating additional power. And after being disconnected from the system, batteries in Zone 4 absorb the extra power while DG gradually reduces the output power, thus maintaining the zonal stable operation. In addition, it can be observed from Fig. 5.8 that all four zones remain at healthy SOC levels during this process.

From the above, it can be conclude that the proposed PMS can effectively distribute power flow within each zone while coordinating the cooperation between adjacent zones to create a reliable, efficient, and resilient ship.

3 Conclusion

To better support the large-scale ships that are in zonal multi-microgrid distributions, a real-time distributed PMS is proposed to ensure efficient and resilient operation under high load fluctuations. The proposed PMS consists of three layers, dividing the large-scale scheduling problem into three pieces to reduce the computational efforts. In addition, the distributed scheme allows each zone to support each other and solve its sub-optimization problem with less communication effort and fast convergence speed. The efficiency of the proposed PMS in regards to power tracking, energy reservation, and enhanced resilience is well validated by comprehensive case studies.

Chapter 6 Conclusion

1 Summary

The overall target of this thesis is to enable reliable and efficient operation of the ship under high-frequency load fluctuations. To this end, real-time power management systems are developed to guide the optimal power allocation between multiple energy sources. Since propulsion loads exhibit different characteristics in different sea states, sailing speeds, and cruising conditions, and considering that vessels of different scales and electrical distributions have different needs, priorities, and goals, power management systems should be able to meet the requirements in all these circumstances. Based on this idea, studies are conducted and effective power management strategies are proposed, which can be concluded as follows,

A comprehensive review about the shipboard power and energy management strategies that are developed based on optimization algorithms is presented. And the generally concerned topics, commonly used algorithms, and the future research trends are discussed.

Real-time power management systems in centralized arrangement is developed for ships that are in radial distributions and with hybrid power sources. By analyzing and calculating the instantaneous equivalent fuel consumption of each component, the PMS optimizes the optimal power splitting between them in real-time to realize the saving of fuels. In addition, by dividing the management scheme into several layers, the complexity of the optimization problem can be largely reduced, which enables improved computing efficiency. Multiple case studies demonstrate that the proposed PMS can guarantee good performance in power tracking, fuel-saving, and energy reservation under different sea states and cruising conditions.

A multi-step load forecasting system suitable for highly dynamic load conditions is proposed. Based on the autoregressive integrated moving average model, the MSLF collects load information for the past several minutes and predicts the load for the next few steps. Several tests prove that the proposed MSLF acquires the same high accuracy as linear prediction and has the ability to perform multi-step prediction under different sea states. In addition, by integrating MSLF, the power tracking delays are avoided and the fuel efficiency is improved.

Real-time power management system in distributed arrangement is developed for ships that are in zonal multi-microgrid distributions and with hybrid power supply. The distributed scheme allows the large-scale optimization problem to be divided into several sub-problems to be solved by each zone, thus significantly reducing the computational effort. Convergence tests prove that the distributed algorithm converges and computes at a fast speed. And the case studies including the normal and faulty conditions prove that the proposed PMS is efficient in fuel-efficiency operation, healthy energy reservation, and high resilience under fluctuating propulsion loads.

2 Future Work

The study of decarbonization for marine transportation is attracting increasing attention and is driving a revolution in power sources from traditional diesel fuels to low-carbon fuels and thus facilitating the development in ship architecture, composition, control, and management. However, there is still a large research gap in the study of ships that are in the zonal multi-microgrid structures. Due to the advantages of low cost, high reliability, and good operational flexibility, future ships are moving towards large-scale and zonal electrical distribution, which brings opportunities and challenges for the development of corresponding PMS and EMS. Its flexible operational modes, bidirectional energy supply, and plug-and-play features put new requirements on energy management. In addition, due to the reason that most zonal distribution-based ships have large scales, it would be inefficient, or even impossible to apply the traditional developed centralized PMSs directly to the ZED-based ships due to the complex system structure, utilization of multiple energy sources, and changeable power flows. The increase in the amount of information largely complicates the computational work. Therefore, specific studies of PMS/EMS for ZED-based ships are a necessity to realize high fuel efficiency, and reliable, resilient, and economically friendly operation. Although this project has addressed this problem by developing a real-time distributed PMS, there are still more issues remaining to be studied and the future research plan is resented in detail as follows.

Optimal sizing and early-stage energy dispatch: Zonal distribution enables more flexible operation, thus offering the opportunities for more efficient ways of sizing and energy dispatching. However, although there has been plenty of research work in this area, rare of them are designed for zonal multi-microgrid ships. Therefore, studies that seek a more efficient and cost-reduced way of configuration and sizing principle for ZED-based ships are necessary. Analysis of historical load profile, future load prediction, energy generation forecasting, global planning, and corresponding distributed energy management system would be useful to realize a greener, more reliable, and economical ship.

Optimal configuration and distributed power management system design: The future trends in ZED-based ships promote research in distributed PMS. In order to achieve a fuel-efficient, reliable, and resilient shipboard power system, studies about the optimal zonal communication configurations, and corresponding energy management strategies are essential for practical applications.

Renewable energy resources integrated shipboard power system: In order to accelerate decarbonization, renewable energy resources such as PV, wind turbines, and fuel cells are encouraged to replace the traditional fuel-consumed gensets. However, the energy generation, lifetime, and cost of RES are affected by environmental and cruising factors. Current studies mostly ignored the characteristics and dynamics of RES, thus having the limitation of practical applications. Therefore, it is necessary to design an effective energy management strategy that can guarantee the optimum environmental and economical investment with consideration of weather, sea states, navigation plans, cruising mission, etc.

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