

Article

Empirical Research to Design Rule-Based Strategy Control with Energy Consumption Minimization Strategy of Energy Management Systems in Hybrid Electric Propulsion Systems

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Abstract

Equivalent energy consumption minimization methods of energy management systems have been implemented as a rule-based strategy to enhance electric propulsion system efficiency. This study compares the efficiencies of different systems by applying variable- and constant-speed generators with battery hybrid systems, measuring fuel consumption. In the same scenario, the variable-speed operation showed a notable improvement of 10.36% compared to the conventional system. However, in the verification of hybrid system efficiency, onshore charged energy cannot be considered a reduction in fuel consumption. Instead, when converting onshore energy usage into equivalent fuel consumption for comparative analysis, both hybrid constant- and variable-speed operation modes achieved efficiency enhancements ranging from 5.5% to 9.79% compared to the conventional, nonequivalent constant-speed operation mode. Conversely, the nonequivalent variable-speed operation mode demonstrated an efficiency that was 5.41% higher than that of the hybrid constant-speed operation mode. In contrast, the battery-integrated variable-speed operation mode indicated a system efficiency approximately equal to that of the nonequivalent variable-speed operation mode. For vessels with load profiles characterized by prolonged periods of idling or low-load operations, a battery-integrated hybrid system could be a practical solution. This study demonstrates the necessity of analyzing load profiles, even when aiming for the optimal operational set points of the generator engine.

Keywords: energy consumption minimization; energy management system; rule-based strategy; electric propulsion system; system efficiency; fuel consumption; variable speed; battery hybrid; load profile



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1. Introduction

1.1. Development of Energy Management System in Hybrid Electric Propulsion Systems

Greenhouse gas reduction technologies are implemented across several vessels, ranging from large to small and medium-sized vessels [1]. Aksöz et al. (2025) demonstrated that ship electrification technology is being applied to ships of various sizes through actual small and medium-sized electric and hybrid ships such as Ellen and Ampere [2]. There are also cases where greenhouse gas reduction technologies are presented not simply as a list of technologies, but as specific application strategies tailored to the size and

characteristics of the vessel [3–5]. These technologies include various research and development efforts related to the propulsion and power systems of environmentally friendly vessels [6]. Yin et al. (2023) comprehensively analyzed renewable energy-based power systems, spatiotemporal prediction, power scheduling, and digital twin technology to propose a technological framework for smartening and reducing carbon emissions in new energy ship power systems [7]. In particular, a study that presented the optimization of power distribution and energy management of hybrid ships using mathematical modeling and actual load profiles showed the potential for fuel savings and improved efficiency [8]. Research on the design of hybrid systems applied to short-distance vessels has made practical contributions [9]. Among these, electric and hybrid electric propulsion systems are utilized as alternatives to environmentally friendly propulsion systems for small- and medium-sized vessels by applying technologies aimed at reducing carbon dioxide emissions through improved system efficiency [10,11]. Bennabi et al. (2021) designed and demonstrated a battery–supercapacitor hybrid propulsion system for a 330 kW river ferry on the Seine River in France, confirming CO₂ reduction effects of approximately 29.7% and 18%, respectively, and suggesting a high-power response plan for short-term operation cycles [12]. To achieve such improvements in system efficiency, the operation of the generator engine should be optimized; however, the integration of a battery system is essential for this purpose [13,14]. Nivolianiti et al. (2024) and Guo et al. (2024) verified and analyzed the effectiveness of ESS integration and energy management systems (EMS) based on actual ship operation data, contributing to increasing the feasibility of hybrid propulsion systems for actual ship applications [15,16]. In the case of hybrid systems incorporating battery systems, the energy management system must be designed based on the battery status and optimal operating points of the generator engine, enabling enhanced control compared with the case of conventional power management systems [17]. Cao, W. (2023) developed an ECMS-filter-based EMS for fuel cell and battery–supercapacitor hybrid ESS, which reduced fuel cell output fluctuations, improved fuel efficiency by 5–6%, and secured robustness to initial battery SOC changes [18]. In addition, Kim (2018), Ünlübayır et al. (2023), and Seenumani et al. (2010) have demonstrated the efficiency improvement and system reliability of hybrid EMS through various empirical and simulation studies, including the optimization of ESS capacity and power distribution, reduction in CO₂ during port operations, and AIS-based load prediction [19–21]. Studies on various control techniques, including the development of controllers for electric propulsion systems, are being conducted [22]. Bennabi et al. comprehensively summarized hybrid propulsion architectures and commercial cases for small vessels, systematizing design guidelines and regulatory response technology trends [22]. Furthermore, Kurniawan et al. (2024) analyzed the architectural characteristics and advantages and disadvantages of series, parallel, and hybrid propulsion systems and reported that model predictive control (MPC) and adaptive control strategies can simultaneously improve the response speed and efficiency of the propulsion system, while ensuring stability under various operating conditions [23]. Technological advancements have been made from PMS to BMS and energy management systems (EMS) [24]. Ghimire et al. (2024) demonstrated fuel savings and improved the space and weight efficiency of hybrid systems according to various control strategies based on actual ship operation data [25], and Chen et al. (2020) confirmed improved power quality and extended battery life by applying integrated optimization techniques and machine learning-based control strategies to a battery–supercapacitor hybrid ESS [26], and numerous studies on battery-integrated hybrid systems are being conducted [27]. Wang et al. (2021) applied a two-stage multi-objective optimization technique to a multi-energy source hybrid ship propulsion system, demonstrating that battery utilization and fuel cell–battery hybrid operation optimize fuel consumption and emissions [28]. Akbarzadeh et al. (2022) and Choi and Kim (2024) si-

multaneously achieved cost and weight efficiency improvements and fuel savings through battery-based hybrid system design and optimal energy management strategies [29,30]. The effectiveness of rule-based control, which applies energy-consumption minimization strategies, has been demonstrated in several studies, evolving beyond traditional equivalent and nonequivalent operating methods [31–33]. For example, Yuan et al. (2016) applied an ECMS to a hybrid electric propulsion tugboat, demonstrating approximately 17.6% fuel savings compared to a traditional rule-based approach [34]. Skjong et al. (2017) designed an EMS including an ESS and compared and evaluated MILP and logic-based algorithms based on actual operating data, demonstrating fuel savings and improved operating efficiency [35]. Additionally, compared with conventional generator configurations, the battery-integrated hybrid system enhances the stability and reliability of the system by utilizing battery systems [36]. Kolodziejski and Michalska-Pozoga (2023) reported that battery energy storage systems (BESS) contribute to fuel savings, emission reductions, and improved power stability by leveling ship loads, utilizing regenerative braking, and providing reserve power [36]. He et al. (2022) demonstrated fuel savings and stable power supply by optimizing BESS installation and operation [37]. They confirmed that EMS optimization in hybrid power systems achieves a stable power supply and reduced operating costs even under load fluctuations [38,39]. Unlike in the case of conventional constant-speed generators, when applying variable-speed generators, effective improvements in energy efficiency are observed within low-load operational zones [40,41]. Ghimire et al. (2022) demonstrated that model predictive control (MPC) and a physics-data-based model fusion framework can improve fuel efficiency and reduce emissions under load fluctuations in a marine hybrid power system integrating a gas engine and batteries [42,43]. They also demonstrated that linking with batteries can simultaneously achieve load responsiveness and greenhouse gas reductions [44]. However, existing studies have shown a lack of experimental comparative verification between the efficiency enhancements of battery-integrated hybrid systems and those of standalone generator systems [45]. It has been pointed out that the lack of systematic verification studies under actual operating conditions limits the generalization of the efficiency and excellence of the battery-integrated system [46,47]. Moreover, studies have shown that variable-speed generators yield a higher system efficiency than constant-speed generators [48]. Tjandra R. et al. demonstrated that variable-speed diesel generators and battery capacity optimization can improve fuel efficiency and reduce unnecessary fuel consumption under load fluctuations [49]. Studies applying a fuel cell–battery hybrid system and NSGA-II-based power distribution optimization demonstrated that fuel savings and emissions reductions can be achieved simultaneously while improving operational performance [50,51]. In addition, it has been confirmed that utilizing MPC-based energy management and reinforcement learning-based energy management strategies can optimize battery charging/discharging and generator operation and maintain fuel efficiency and emission reduction effects even in various operating environments [52–55]. Studies on fuel cell–battery hybrid propulsion and multi-objective optimization have demonstrated through simulations and empirical cases that it can reduce energy consumption and emissions while ensuring economic efficiency [56,57]. Finally, integrated analysis and operational simulation studies have confirmed that battery–fuel cell hybrid propulsion and battery–diesel integrated strategies can achieve fuel savings and improved energy efficiency [58–60].

1.2. Necessity for Experimentally Evaluating Energy Management in Hybrid Electric Propulsion Systems

This study addresses the following questions: What is the efficiency of a power system for a battery hybrid system compared with that of conventional systems? Have experimental studies on existing battery hybrid systems been conducted as part of this study? To

what extent does the application of variable-speed generators, compared with conventional constant-speed generators, yield effective efficiency improvements in a generator engine that exhibits various efficiencies depending on output? Do the control rules necessary for these operations function safely? Whereas experimental applications involving various load profiles provide highly reliable data, this study experimentally addresses these questions based on the load profile of a specific small-to-medium-sized vessel.

We designed a control system for a hybrid electric propulsion system that does not utilize only general hybrid modes based on the battery state of charge (SOC) and load. Rather, we intended to maximize the optimal operation of the generators while validating system efficiency through battery intervention. Furthermore, we aimed to experimentally assess the extent to which changes in this system affect fuel consumption while also comparing improvements in the efficiency of the electric propulsion system when the proposed control system and conventional control systems are applied.

To this end, the testbed established for the land-based validation of the battery hybrid electric propulsion system comprises a power generation system, power distribution system, battery system, Power Conversion System/Power Conditioning System (PCS), and load bank devices (propulsion drive, motor, and load). An EMS was developed and implemented to control the power generation and distribution systems, and land-based validation was conducted to ascertain the normal operation of the hybrid electric propulsion system for vessels, as well as to confirm system stability and energy efficiency improvements.

2. Methodology

To address the aforementioned fundamental questions, our findings are validated using the procedures outlined below.

First, we selected a diesel-powered coastal vessel as a comparative subject to experimentally demonstrate the battery hybrid electric propulsion system and determine the specifications of the system. Second, we designed optimal control rules based on an analysis of the system specifications and load profiles and implemented an energy management system that incorporates these rules. Third, we established a land-based hybrid electric propulsion system and measured the load characteristics and fuel consumption following the load profiles. Finally, we evaluated the fuel consumption by comparing the efficiency of the battery-integrated system with that of conventional energy sources. Additionally, we identified the differences in various system configurations through a comparative operation of variable- and constant-speed generators. This study aims to demonstrate the superior efficiency of the battery-integrated hybrid and variable-speed generation systems compared with conventional diesel propulsion systems.

2.1. Step 1: Selection of Comparative Vessels and System Specifications

A cruise vessel operating along the domestic coast was selected, as shown in Figure 1, to analyze load fluctuations during sailing. The operational phases were defined as departure/arrival and normal navigation phases. The output characteristics of the diesel generator and battery system were assessed to apply the load variations in the target vessel to a land-based validation testbed, leading to the development of load scenarios. Given that the route exhibits consistent variability, the application of a generator and battery-integrated hybrid system enables an effective operation. As the load levels differed, an EMS was developed, considering the required duration and persistence of the load fluctuation periods. The load scenarios were categorized into two types: those utilizing the conventional generator parallel operation for the propulsion system and those implementing the EMS developed for the battery hybrid electric propulsion system in this study. To ensure

smooth testing, the output simulation conditions of each power source were configured within the EMS, enabling load simulation following the established control logic.



Figure 1. Battery hybrid electric propulsion vessel [61].

2.2. Step 2: Design of Optimal Control Rules Based on System Specifications and Load Profiles

In energy management systems equipped with two generators, loads on the generators are configured to operate under either equivalent or nonequivalent loading conditions, as described below. However, to enhance system efficiency, one generator is operated at optimal levels, and the other is used as a backup in a nonequivalent method.

$$P_{Load} = P_{Generator_1} + P_{Generator_2} \quad (1)$$

In this approach, the operation of the remaining low-load generators imposes limitations on system efficiency improvement, requiring the operation of a hybrid system integrated with a battery system.

For battery hybrid electric propulsion systems, a rule-based strategy is designed based on the battery SOC, generator capacity, and the ship's load profile, and the load is controlled as shown in the equations below.

$$P_{Load} = P_{Generator} + P_{Battery} \quad (2)$$

$$\text{If battery only mode, } P_{Load} = P_{Battery} \quad (3)$$

$$\text{If generator only mode, } P_{Load} = P_{Generator} \quad (4)$$

$$\text{If hybrid mode, } P_{Load} = P_{Generator} + P_{Battery} \quad (5)$$

$$\text{If power boost mode, } P_{Load} = P_{Generator} + P_{Battery} \quad (6)$$

- Operation mode

Under low-load conditions, either the battery-only operation mode or hybrid mode is used, whereas the power-boost mode is employed during high-load conditions. If the initial battery charge is depleted, the battery must be charged using a generator, as shown in Table 1.

Table 1. Decision logic of operation modes based on SOC and load.

SOC	$P_{Load} \leq P_{Low}$	$P_{Low} < P_{Load} < P_{High}$	$P_{High} \leq P_{Load}$
$SOC_{Battery} \leq SOC_{Min}$	Generator only	Generator only	Generator only
$SOC_{Min} < SOC_{Battery} \leq SOC_{Max}$	Battery only	Hybrid	Power boost mode
$SOC_{Max} < SOC_{Battery}$	Hybrid	Battery only	Hybrid

- Battery status

The battery operates by charging and discharging based on the aforementioned mode conditions and the defined minimum and maximum SOC values, as indicated in Table 2.

Table 2. Battery status under SOC and load conditions.

SOC	$P_{Load} \leq P_{Low}$	$P_{Low} < P_{Load} < P_{High}$	$P_{High} \leq P_{Load}$
$SOC_{Battery} \leq SOC_{Min}$	Charging (with alarm)	-	Idle (with alarm)
$SOC_{Min} < SOC_{Battery} \leq SOC_{Max}$	Discharging	Charging & Discharging	Discharging
$SOC_{Max} < SOC_{Battery}$	Discharging (with alarm)	Battery only(discharge)	Discharging (with alarm)

- Engine status

In the case of engines, depending on the battery SOC and load, they are divided into a stationary state, a variable state, an optimal operation state, and a maximum operation state. In order to improve system efficiency, it is an important factor to operate the generator in the optimal operation state, so if the generator's operating point is lower than the optimal load section, it can be seen as more efficient to arbitrarily command the generator to the optimal operation point and charge the battery system, as presented in Table 3.

Table 3. Generator status under SOC and load conditions.

SOC	$P_{Load} \leq P_{Low}$	$P_{Low} < P_{Load} < P_{High}$	$P_{High} \leq P_{Load}$
$SOC_{Battery} \leq SOC_{Min}$	$P_{Optimum}$	$P_{Variable}$	$P_{Maximum}$
$SOC_{Min} < SOC_{Battery} \leq SOC_{Max}$	P_{Stop}	$P_{Variable}$	$P_{Maximum}$
$SOC_{Max} < SOC_{Battery}$	P_{Stop}	$P_{Variable}$	$P_{Maximum}$

However, in operational load ranges, excluding the optimal operating mode of the energy source, these modes can affect system efficiency. This study aims to experimentally validate an enhanced design methodology for the optimal operating command generation of energy sources and compares improvements in system efficiency achieved through variable- and constant-speed operations.

2.3. Step 3: Construction of Hybrid Electric Propulsion System for Land-Based Demonstration System Diagram

To verify the efficiency deviation between variable and constant speeds in the conventional operation mode and the proposed mode, the system as shown in Figure 2 was tested in three operation modes: generator-only, battery-only, and generator–battery modes.

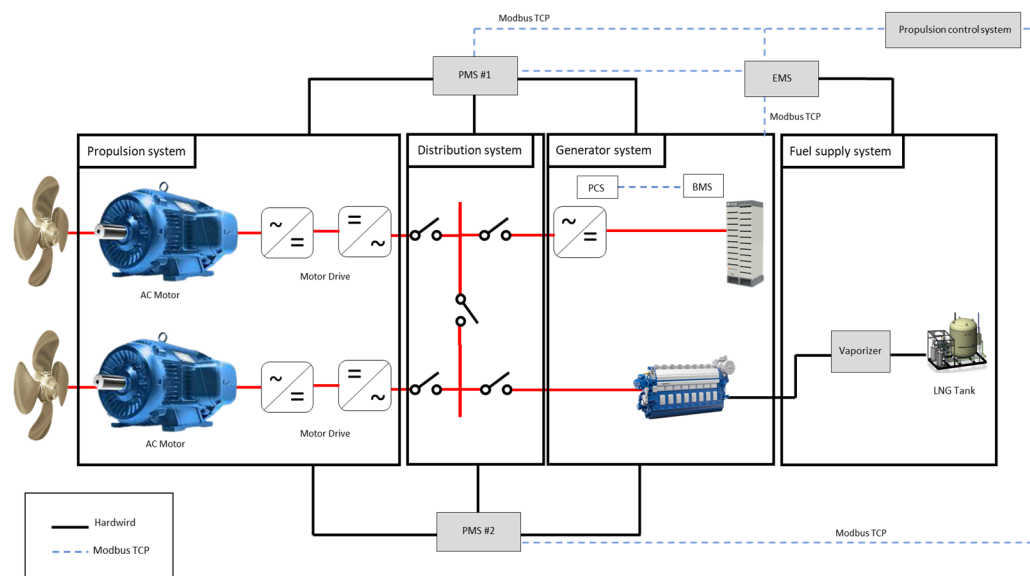


Figure 2. Schematic electric hybrid power system comprising two generator engines and a battery.

2.4. Step 4: Characteristics of Load Sharing and Fuel Consumption Measurement Based on Controller Application

In this paper, the fuel consumption was measured using a flowmeter with a correction factor for each system according to the operating profile by operating the experimental generator in real time by taking the actual ship's operating road profile pattern. The data transmitted in kg/s per second is converted into [g/s], and the integrated data is calculated as the total fuel oil consumption.

3. Result

3.1. Selection of Comparative Vessels and System Specifications

A coastal vessel, the ferry “Eunhasu No. 5”, operating in the Taejongdae area of Busan, South Korea, was selected for this study. The operational load characteristics shown in Figure 3 during normal seagoing, port in/out, and sightseeing activities were analyzed to design a system for achieving optimal efficiency in the energy sources.



Figure 3. Voyage route of reference vessel.

For the empirical testing of the land-based testbed, the outputs of each operating mode were scaled down to half and adjusted accordingly, as shown in Figure 4. Two diesel engine synchronous generators, rated at 400 kW, 440 V, and 1800 rpm, along with a battery system, were selected as the power sources for the vessel's propulsion system as shown in Figure 5. The battery system consisted of five racks, each comprising 24 modules. Figure 4 shows the overall load profile of the vessel over time.

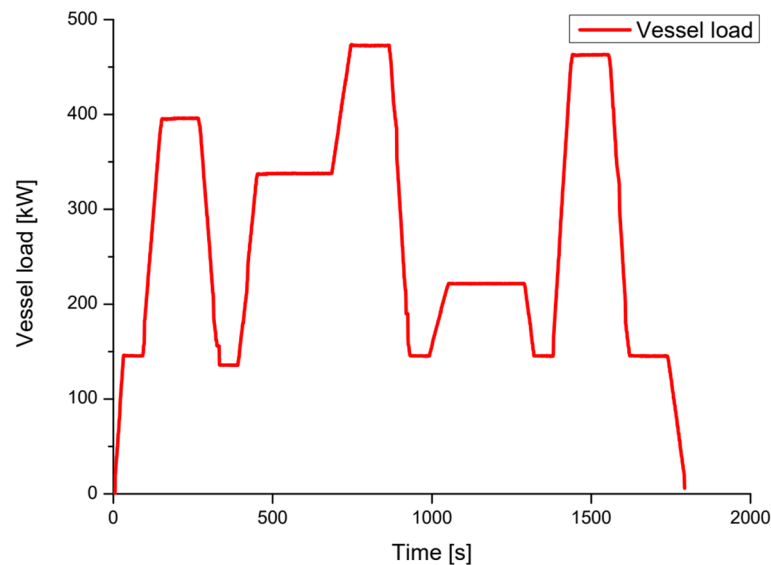


Figure 4. Operating profile of reference vessel.



Figure 5. Test bed for testing proposed generator-battery hybrid system.

3.2. Design of Optimal Control Rules Based on System Specifications and Load Profiles

Unlike conventional control rules, the control rules for the proposed EMS for the battery-integrated hybrid system are as follows: The proposed control rules are designed to maintain the maximum number of optimal operating set points across the entire operational range of the energy sources while minimizing energy consumption, as shown in Tables 4–6.

$$P_{Load} = P_{Generator} + P_{Battery} \quad (7)$$

$$\text{If battery only mode, } P_{Load} = P_{Battery} \quad (8)$$

$$\text{If generator only mode, } P_{Load} = P_{Generator} \quad (9)$$

$$\text{If hybrid mode, } P_{Load} = P_{Generator} + P_{Battery} \quad (10)$$

Table 4. Decision logic of operation modes based on SOC and load.

SOC	$P_{Load} \leq P_{Low}$	$P_{Low} < P_{Load} < P_{High}$	$P_{High} \leq P_{Load}$
$SOC_{Battery} \leq SOC_{Min}$	Generator only	Generator only	Generator only
$SOC_{Min} < SOC_{Battery} \leq SOC_{Max}$	Battery only	Generator only	Hybrid (Gen. + Batt.)
$SOC_{Max} < SOC_{Battery}$	Battery only	Generator only	Hybrid (Gen. + Batt.)

Table 5. Battery status under SOC and load conditions.

SOC	$P_{Load} \leq P_{Low}$	$P_{Low} < P_{Load} < P_{High}$	$P_{High} \leq P_{Load}$
$SOC_{Battery} \leq SOC_{Min}$	Charging (with alarm)	-	Idle (with alarm)
$SOC_{Min} < SOC_{Battery} \leq SOC_{Max}$	Discharging	Charging or idle	Discharging
$SOC_{Max} < SOC_{Battery}$	Discharging (with alarm)	Idle	Discharging (with alarm)

Table 6. Generator status under SOC and load conditions.

SOC	$P_{Load} \leq P_{Low}$	$P_{Low} < P_{Load} < P_{High}$	$P_{High} \leq P_{Load}$
$SOC_{Battery} \leq SOC_{Min}$	$P_{Optimum}$	$P_{Optimum}$	$P_{Optimum}$
$SOC_{Min} < SOC_{Battery} \leq SOC_{Max}$	P_{Stop}	$P_{Optimum}$	$P_{Optimum}$
$SOC_{Max} < SOC_{Battery}$	P_{Stop}	$P_{Optimum}$	-

The engine was designed to operate at optimal loads across all operational ranges, excluding the battery-only operating period, and could be assisted by a battery in high-load regions. Unlike the previously presented fundamental control rules for a hybrid system, the commands for the operation of the energy sources are directed to achieve the maximum optimal operation.

3.3. Establishment of Hybrid Electric Propulsion System for Land-Based Validation

In addition to the energy sources and battery system, a 1-MW PCS for battery charging and discharging was established, as shown in Table 7 and Figure 5. The system comprised a switchboard with circuit breakers, voltage and current measurement devices, a motor drive system, a 400 kW propulsion motor, a load bank, and a fuel flowmeter for fuel measurement, as presented in the table and figure below.

Table 7. Specifications of hybrid electric propulsion system.

No.	Description	Spec	QTY	No.	Description	QTY
1	Diesel generator	400 kW/440 V/1800 rpm	2	5	Motor drive unit	2
2	Battery system	400 kW	2	6	Load(R)	1
3	Distribution system	Distribution system	1	7	Flowmeter	4
4	Propulsion motor	400 kW	2	8	Energy management system	1

3.4. Characteristics of Load Sharing and Fuel Consumption Measurement Based on Controller Application

3.4.1. Operating Characteristics of Load Sharing for Constant-Speed Generators Based on Conventional Nonequivalent Load Sharing Methods

To improve system efficiency in vessel loads, in the case of a conventional system, one generator operates sufficiently close to the optimal operating point, and the remaining generators operate under low-load conditions, as indicated in Figure 6. Because constant-speed generators are employed, they maintain a constant frequency and speed at 1800 rpm,

as shown in Figure 7. However, they exhibit significantly reduced efficiency during low-load operations, presenting inherent limitations.

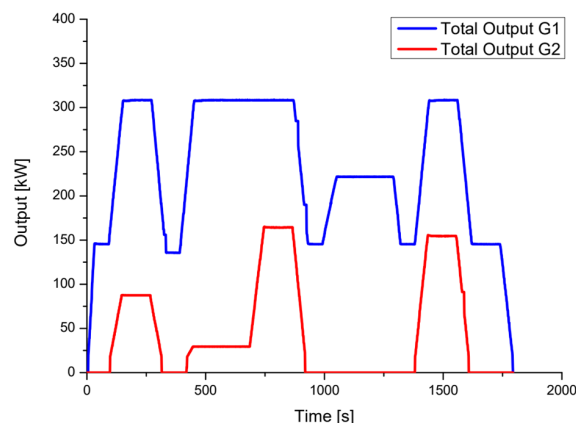


Figure 6. Operating characteristics of output for constant-speed generators.

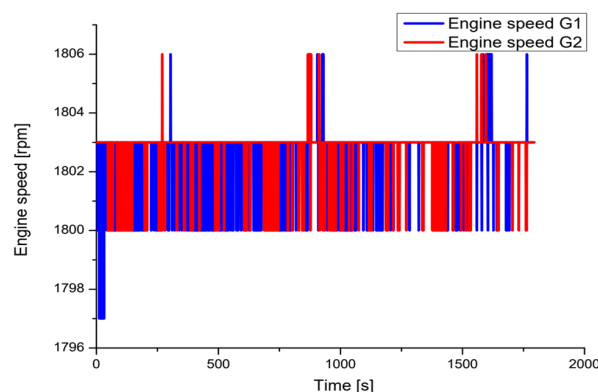


Figure 7. Operating characteristics of RPM for constant-speed generators.

3.4.2. Operating Characteristics of Load Sharing for Variable-Speed Generators Based on Conventional Nonequivalent Load Sharing Methods

To address the limitations of constant-speed generators, operating energy sources at variable speeds enables changes in speed and frequency under low-load conditions, leading to improved fuel efficiency in the low-load range, as shown in Figures 8 and 9. However, the low-load operation of auxiliary generators, because of their nonequivalent operation, significantly decreases the overall efficiency of the system.

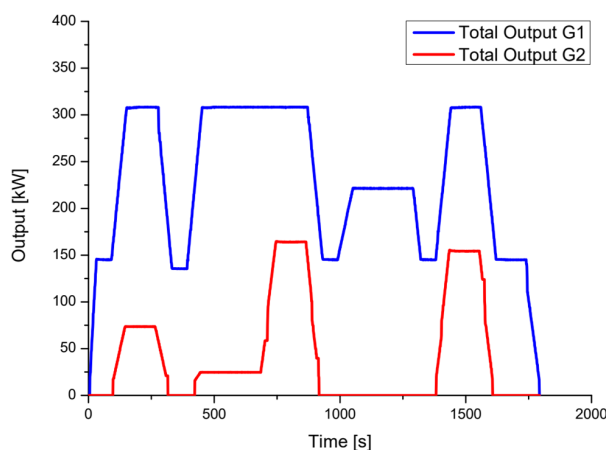


Figure 8. Operating characteristics of output for variable-speed generators.

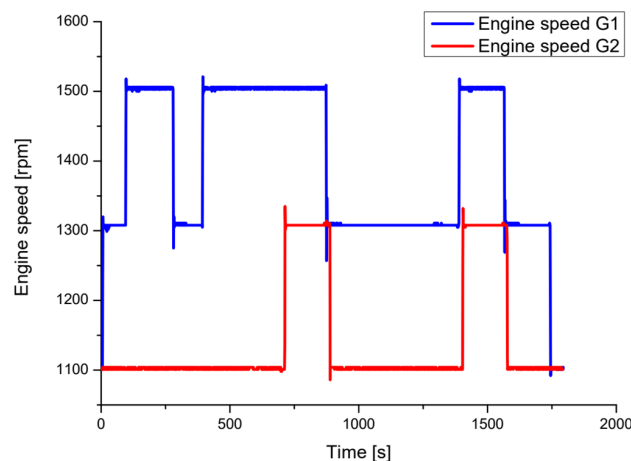


Figure 9. Operating characteristics of RPM for variable-speed generators.

3.4.3. Battery-Integrated Constant-Speed Generator Hybrid System with Proposed Control Rules

To enhance system efficiency, the operation of the battery-integrated hybrid system incorporating the proposed control rules was experimentally evaluated, as outlined below. Under the experimental conditions shown in Figures 10 and 11, battery charging was performed following land-based charging standards. Throughout the operational range, one generator operated under optimal conditions, and the charging and discharging of the battery facilitated the optimal operation of the energy source, thereby improving the overall system efficiency. While the speed and frequency exhibited consistent operational patterns, low efficiency was observed during low-load operations at specific intervals.

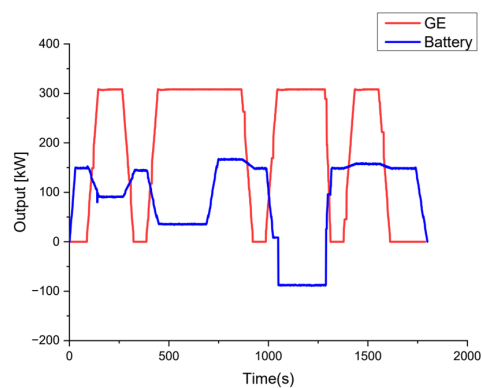


Figure 10. Comparison of outputs between battery hybrid system and generator.

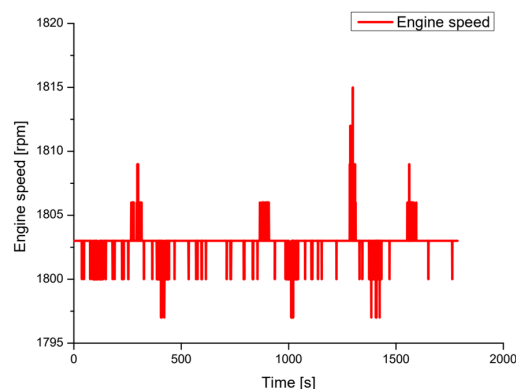


Figure 11. Operating characteristics of engine speed for battery-integrated variable-speed generator hybrid system.

3.4.4. Battery-Integrated Variable-Speed Generator Hybrid System with Proposed Control Rules

For a battery-integrated hybrid system that incorporates variable-speed generators, which mitigate the disadvantages of constant-speed generators, system efficiency can be maximized by controlling the speed and frequency of the energy sources, even during low-load intervals, as shown in Figures 12 and 13. This experiment was conducted under the assumption that battery charging was performed following land-based charging standards.

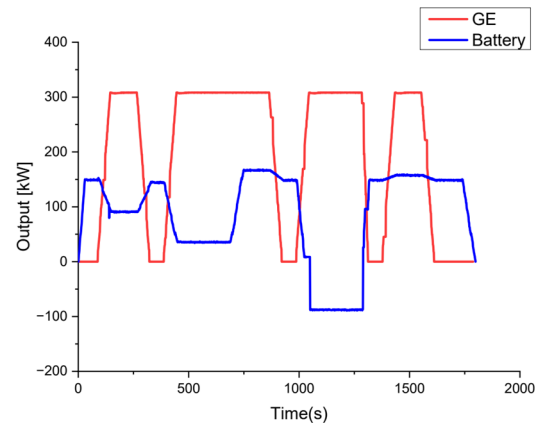


Figure 12. Operating characteristics of output for battery-integrated variable-speed generator hybrid system.

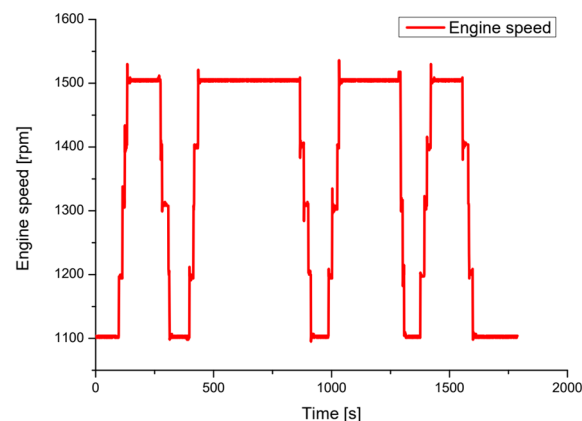


Figure 13. Operating characteristics of engine speed for battery-integrated variable-speed generator hybrid system.

3.5. Comparison Evaluation Based on Fuel Consumption

As demonstrated in the abovementioned experiment, this study compared and analyzed the operational characteristics of four different system configurations and generator engine operating modes using the same load profile, as shown in Table 8.

Table 8. Comparison of battery-integrated hybrid variable-speed and constant-speed generators with conventional constant-speed and variable-speed generators.

	Conventional Constant	Conventional Variable
Hybrid Constant	−33.87%	−26.23%
Hybrid Variable	−38.15%	−31.01%

For parallel operation with two generators not connected to a battery system, assuming identical nonequivalent operation for the vessel load, fuel consumption was 30.38 kg in

the constant-speed mode and 27.23 kg in the variable-speed mode. This indicates a 10.36% reduction in fuel consumption in the variable-speed mode compared with the constant-speed mode, under the same load and system conditions, by simply changing the generator operating mode.

Operation using a single generator was possible in a system integrated with a battery. When commanded to operate in the optimal mode, the constant-speed mode consumed 20.09 kg of fuel, whereas the variable-speed mode consumed 18.78 kg. This shows a 6.48% reduction in fuel consumption in the variable-speed mode when integrated with a battery system.

The variable-speed mode exhibits a lower efficiency than the parallel operation of the two generators because the battery-integrated system operates the single generator continuously in the optimal mode, rendering further efficiency improvement almost impossible.

A comparison of these system conditions showed that, compared with the conventional nonequivalent constant-speed generator, the battery-integrated hybrid variable-speed generator reduced fuel consumption by 38.15%.

4. Discussion

The operation of the system differs depending on whether the battery system is fully charged onshore or using power generated onboard the vessel. Additionally, the carbon dioxide emissions produced per unit of energy from onshore power sources help to determine whether this charging method is environmentally friendly for battery-integrated hybrid systems. To assess this, the first method involves converting the energy consumption of the battery system into fuel consumption and comparing pure energy efficiency improvements. This is achieved by calculating the fuel consumption of the generator at the optimal operating point and substituting this into the power consumption to inversely calculate the total fuel consumption, as indicated in Table 9.

Table 9. Improvement of efficiency, compared to the nonequivalent constant-speed operation mode.

	Conventional Constant	Conventional Variable
HYBRID Constant	−5.50%	5.41%
HYBRID Variable	−9.79%	0.64%

In this scenario, the total charging energy was 177,174 kWh, and the total discharge energy was 21,087 kWh. When these values were converted into fuel consumption, the charging process consumed 9.7 kg of fuel, whereas the discharging process resulted in fuel savings of 1.16 kg. When comparing the energy consumption used for battery charging and discharging with the operating energy consumption of the generator, the hybrid constant-speed and variable-speed operation modes improved efficiency by 5.5% to 9.79% compared with that of the nonequivalent constant-speed operation mode. However, the nonequivalent variable-speed operation mode demonstrated 5.41% higher efficiency than the hybrid constant-speed mode, indicating that even in the battery-integrated hybrid mode, efficiency decreases during low-load operation under constant-speed control. Moreover, the battery-integrated variable-speed operation mode exhibited a system efficiency similar to that of the conventional nonequivalent variable-speed mode.

This study experimentally investigates how the system efficiency of hybrid electric propulsion systems for ships varies depending on battery integration, generator type (constant-speed vs. variable-speed), and the applied control strategies. To validate this, actual ship operating load profiles were used, and the results demonstrated that even without battery integration, variable-speed generators alone can significantly improve the efficiency of electric propulsion systems. Experimental validation considering various

vessel types, ship categories, operating conditions, and battery lifetimes will be addressed in future research. This demonstrates the effectiveness of the variable-speed operation mode for energy sources, particularly in improving efficiency under low-load operating conditions. Additionally, the battery-integrated system may influence system efficiency depending on the characteristics of the load profile, although this impact can be minimal. However, in vessels with prolonged idle operation or extended low-load operation profiles, battery-integrated hybrid systems are particularly effective.

When selecting and determining the capacity of a battery system, the overall system efficiency should be considered based on the load profile and the impact of battery usage on capital expenditure (CAPEX). The study findings will contribute to making such decisions. Furthermore, when utilizing shore-based charging, power generation efficiency should be considered a crucial factor.

However, this study did not account for the effects of ship generator engines and battery aging, and its limitations stem from the use of a single load profile for each vessel. Future research requires additional experimental studies that consider various ship types, operating environments, and battery life effects.

Accordingly, when considering only the energy used for discharging, a comparison of efficiency shows that the battery-integrated variable-speed generator exhibits a 34.34% improvement in efficiency compared with that of the conventional nonequivalent constant-speed generator. This study also suggests that verifying the effectiveness of the battery system involves considering the application of the battery system with an operation algorithm for each power source mode, as well as the influence of battery energy charging methods on system efficiency. Additionally, the design of the battery system depends on analyzing load profiles to improve the system.

5. Conclusions

This study examined the operating modes of energy sources applied to small- and medium-sized vessels, focusing on improving conventional nonequivalent operating modes. Fuel consumption measurements confirmed that, compared to the constant-speed mode, efficiency improvements in the variable-speed operating mode resulted in a 10.36% improvement under the same scenario as the selected vessel.

However, owing to the efficiency reduction of the auxiliary generator in nonequivalent operation, the system transitioned to a battery-integrated hybrid system. Diverging from the conventional method of operating energy sources under various load conditions, the system was operated using the proposed optimal control rules. Furthermore, the study experimentally demonstrated efficiency improvements in both constant-speed and variable-speed operating modes.

The results indicated that, compared with the nonequivalent constant-speed operation, when operating with a variable-speed generator in the hybrid system, a 38.15% improvement in system efficiency was achieved. However, this reduction in fuel consumption did not account for the energy required to charge and discharge the battery system using shore power. To address this, the fuel consumption per unit of electrical energy was calculated and compared under the assumption that electricity was generated under the optimal operating conditions of the generator. The analysis showed that, compared with the nonequivalent constant-speed operation, the hybrid constant-speed and variable-speed operation modes improved the efficiency by 5.5% to 9.79%. However, the efficiency of the conventional nonequivalent variable-speed mode was 5.41% higher than that of the hybrid constant-speed mode, indicating that even with a battery-integrated hybrid system, efficiency decreases during low-load operation. Moreover, the battery-integrated variable-speed mode exhibited a system efficiency comparable to that of the conventional

nonequivalent variable-speed mode, demonstrating the effectiveness of the variable-speed mode for energy sources. This also indicated that a battery system with a variable-speed mode in a low-load operation can provide efficiency improvements, although the results may vary depending on the characteristics of the load profile.

In vessels with prolonged idle operation or extended low-load operation profiles, battery-integrated hybrid systems are particularly effective. This study highlights that even with optimal operating setpoints, the characteristics of the load profile should be carefully analyzed when operating the system. This is a critical factor when selecting and determining the capacity of a battery system, as it significantly affects both operational expenditure and CAPEX. Our study findings highlight the need to consider power generation efficiency when utilizing shore-based charging. The optimal design of control rules tailored to the load profile is essential for EMS design.

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