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Research Paper

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Study on Equivalent Consumption Minimization Strategy Application in PTI–PTO Mode of Diesel–Electric Hybrid Propulsion System for Ships

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Abstract : *In Korea, five major ports have been designated as sulfur oxide emission control areas to reduce air pollutant emissions, in accordance with Article 10 of the "Special Act on Port Air Quality" and Article 32 of the "Ship Pollution Prevention Regulations". As regulations against vessel-originated air pollutants (such as PM, CO2, NOx, and SOx) have been strengthened, the Ministry of Oceans and Fisheries(MOF) enacted rules that newly built public ships should adopt eco-friendly propulsion systems. However, particularly in diesel–electric hybrid propulsion systems,the demand for precise control schemes continues to grow as the fuel saving rate significantly varies depending on the control strategy applied. The conventional Power Take In–Power Take Off(PTI–PTO) mode control adopts a rule-based strategy, but this strategy is applied only in the low-load range and PTI mode; thus, an additional method is required to determine the optimal fuel consumption point. The proposed control method is designed to optimize fuel consumption by applying the equivalent consumption minimization strategy(ECMS) to the PTI–PTO mode by considering the characteristics of the specific fuel oil consumption(SFOC) of the engine in a diesel–electric hybrid propulsion system. To apply this method, a specific fishing vessel model operating on the Korean coast was selected to simulate the load operation environment of the ship. In this study, a 10.2% reduction was achieved in the MATLAB/SimDrive and SimElectric simulation by comparing the fuel consumption and CO2 emissions of the ship to which the conventional rule-based strategy was applied and that to which the ECMS was applied.*

Key Words : *Air pollutants, Eco-friendly ship, Diesel–Electric hybrid propulsion ship, PTI–PTO mode, Equivalent consumption minimization strategy*

1. Introduction

Regulations on air pollution from ships are being strengthened both internationally and domestically. In the sulfur oxide emission control area designated for five major ports according to the "Rules on Pollution Prevention in Ships", the sulfur content was applied to 0.1% or less only when ships were anchored or berthed in ports. However since January 1, 2022, standards have been strengthened to apply to all ships entering and leaving the emission control area, in accordance with Article 10 of the "Special Act on Port Air Quality" and Article 32 of the "Ship Pollution Prevention Regulations"; emission regulations for air pollutants (such as PM, CO2, NOx, and SOx) from ships are being strengthened.

The main cause of these air pollutants is that in the case of a mechanical propulsion system that uses fuel for propulsion, the fuel is burned by the main engine and carbon dioxide is generated from the carbon contained in the fuel. Owing to the characteristics of the engine, when it is operated in a low-load section, incomplete combustion occurs relatively frequently, resulting in poor fuel efficiency. Thus, the output is low compared to the fuel consumed. Driving in this section should be avoided as much as possible because it is inefficient and generates more exhaust gas than that in other ranges. However, driving at low speeds is inevitable when navigating through narrow waterways or owing to speed limit regulations in ports. In addition, in the case of fishing boats, the generator must be started, and the prime mover must be operated with a low load because of the amount of power required for operation (Kim et al., 2012).

As a way to reduce emissions, interest in electric powered ships, among eco-friendly ships, is growing. Accordingly, the Ministry of Oceans and Fisheries established the "Eco-friendly Public Vessel Conversion Plan" in October 2019 to convert all public vessels (140 in total) into eco-friendly vessels by 2030. Although the technological development of batteries and fuel cells is in progress to transform ships into eco-friendly ships, they have the disadvantage of being bulky and have space restrictions when

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installed on ships. The number of cases of applying diesel–electric hybrid propulsion systems has been increasing (Zhang et al., 2015).

In the field of research on eco-friendly ships, a diesel–electric hybrid propulsion system was introduced by adding a propulsion motor to the existing mechanical propulsion system, in which the battery operation mode of the electric propulsion system was used to avoid the low-load operation of the engine(Xiao et al., 2016).

Therefore, in this study, along with a study on the diesel–electric hybrid propulsion system, the equivalent consumption minimization strategy (ECMS) was applied to control the fuel consumption according to the fuel consumption characteristics of the engine. For the experiment, one domestic coastal fishing vessel was selected as the target vessel based on the load operating environment of the vessel actually navigating the coast in Korea. Through the simulation program, the fuel consumption and CO2 emissions of ships to which the existing rule-based strategy was applied and those to which the ECMS was applied were compared and analyzed(Sezer et al., 2011),(Zeng et al., 2018).

2. Components of a hybrid propulsion system

The propulsion system studied herein is a parallel-type complex propulsion system, and the components include a battery, DC/DC converter, DC/AC inverter, and shaft generator/motor, as shown in Fig. 1. In the electric propulsion method, the propeller propels the ship while the shaft of the propeller rotates when the force is transmitted to the gearbox using the rotational force from the shaft generator motor, and the mechanical propulsion method propels the propeller with the engine. A system comprising these two methods is called a hybrid propulsion system.

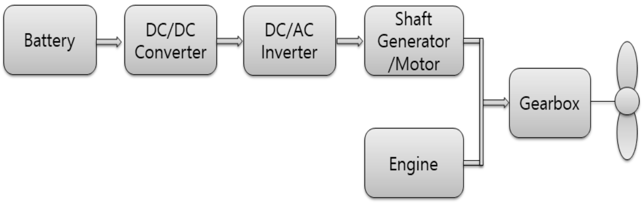

Fig. 1. Structure of a hybrid propulsion system.

2.1 Battery

Table 1 presents the battery design values for the simulation in this study.

Table 1. Battery specifications

Battery Specification	
Nominal voltage	350 [V]
Rated capacity	1314 [Ah]
Nominal discharge current	365 [A]

In the simulation, the state of charge (SOC) of the battery was calculated as expressed in Equation (1).

$$SOC(t) = SOC(0) - \frac{\eta_i}{Q_n}\int_0^t i(\tau) \cdot d\tau \tag{1}$$

η_i denotes the cell coulombic efficiency, $i(t)$ denotes the instantaneous current, and $Q_n = 3600 \times Ah$ denotes the nominal Ah capacity of the cell. In general, η_i is calculated as the ratio of the amount of charge entering the cell during charging to the amount of charge going out during discharge, as shown in Equation (2)(Michel et al., 2015).

$$\eta_i = \frac{Q_{disch.}(Ah)}{Q_{charge}(Ah)} \times 100\% \tag{2}$$

Because the engine room of a fishing vessel is not large, a lithium-ion battery with a small weight and volume among the batteries was selected to design the simulation.

2.2 Power converter

Fig. 2 presents the structure of the power converter. It consists of a battery, DC/DC converter, main inverter, and induction machine.

2.2.1 DC/DC Converter

When the output of the battery is directly used, the magnitude of the voltage decreases as it discharges; thus, the output voltage becomes unstable. In addition, the current becomes unstable; thus, the stability of the system is not secured. Therefore, a DC/DC converter, as shown in Fig. 2, is used to ensure system stability. In this study, a bidirectional DC/DC converter capable of charging and discharging was used. In the discharge mode, the converter controller is designed to boost the voltage in the boost mode to operate a high-voltage electric device using the low voltage of the battery. In the charge mode, the converter controller is designed to charge the voltage by stepping down the voltage in the buck mode.

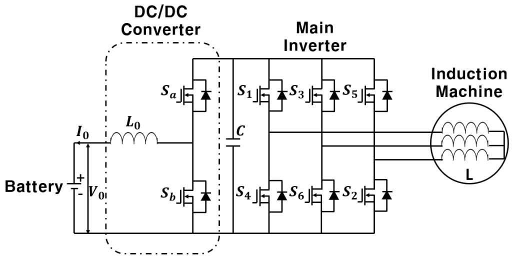

Fig. 2. Structure of a power conversion system.

2.2.2 Bidirectional power converter

In this study, the bidirectional power converter consists of a rectifier and an inverter, and its role differs depending on the battery charging and discharging modes. In the battery charge mode, the shaft generator motor becomes a generator and is used as a rectifier. In the battery discharge mode, the shaft generator motor becomes a motor and is used as an inverter. As shown in Fig. 2, it has a three-phase full-bridge inverter structure and the controller is configured using space vector pulse width modulation (SVPWM) method. The switch of the power conversion device is operated by the controller and DC or AC power is generated.

The inverter converts DC power into AC power and controls the speed of the motor by varying the voltage/frequency. In addition to controlling the speed, the use of an inverter has the advantage of protecting the motor by limiting the current and suppressing the large starting current that occurs instantaneously during starting.

2.3 Shaft generator motor

Table 2 lists the items and parameters for the design of the shaft generator motor.

The shaft generator motor can be operated as a motor using the power of the energy storage system (ESS) battery or it rotates by the generated rotational force to produce electricity.

The following equations represent the dynamic model of the shaft generator motor: The formulas for the output are shown in (3) and (4), and the formula for torque is shown in (5). Through these equations, the stator-side converter maintains a constant DC BUS voltage and enables the independent control of active and reactive power. The converter on the rotor side analyzes the rotor current in the direction toward the stator flux, separates the torque and the rotor excitation current, and calculates the rotor reference voltage to drive the shaft generator motor at the desired speed, which is used to drive the gate of the PWM converter.

Table 2. Shaft generator motor specifications

Item	Value	Item	Value
Nominal power	115 [KVA]	X_m	6.25 [Ω]
V_{rms}	380 [V]	R_r	0.085 [Ω]
Frequency	60 [Hz]	X_{lr}	0.175 [Ω]
R_s	0.01485 [Ω]	Pole pairs	2
X_{ls}	0.085 [Ω]		

$$P_s = \frac{3}{2}(V_{ds}i_{ds} + V_{qs}i_{qs}) \tag{3}$$

$$Q_s = \frac{3}{2}(V_{qs}i_{ds} - V_{ds}i_{qs}) \tag{4}$$

$$T_e = -\frac{3}{2}\frac{p}{2}(\lambda_{ds}i_{qs} - \lambda_{qs}i_{ds}) \tag{5}$$

2.4 Internal combustion engine (ICE)

Table 3. ICE specifications

ICE Specifications	
Maximum power	465 [kW]
Rated speed	1800 [rpm]
Maximum torque	2466 [N·m]

An ICE is a heat engine in which combustion occurs in a combustion chamber. Rotation occurs when the crankshaft is driven by the explosive force generated by the combustion in the ICE. The simulation was performed with the parameters presented in Table 3 by applying a four-cycle engine, such as the main engine of a ship.

3. Energy management system (EMS)

The diesel - electric hybrid propulsion system is controlled through an EMS as shown in Fig. 3. A system that integrates the control of devices such as batteries, main engines, and gearboxes required to generate the propulsion speed and the output required for the propeller is required. Therefore, an optimal controller with an EMS is required. In this study, the ECMS was added to the conventional rule-based strategy and applied to a diesel–electric hybrid propulsion system.

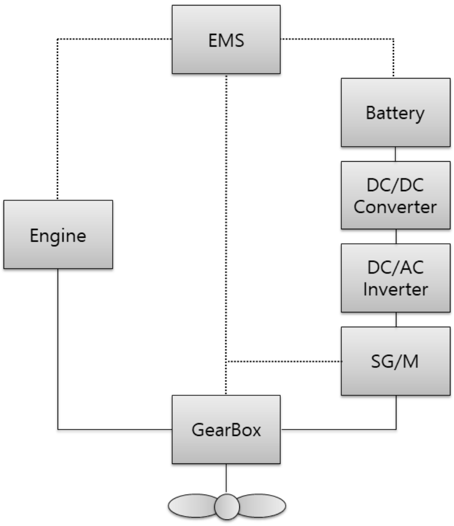

Fig. 3. Schematic of an EMS.

3.1 Operation mode

There are four operating modes for driving the engine, battery, gearbox and shaft generator motor in the diesel–electric hybrid propulsion system, as shown in Fig. 4.

First, in the mechanical mode, mechanical energy is transferred to the propulsion machine using only the engine.

Second, in the PTH mode, power is transmitted to the propulsion machine by supplying electric energy to the motor using only a battery or a generator.

Third, in the PTO mode, some of the energy generated from the propulsion machine is supplied to the shaft generator to store electrical energy in the ESS.

Finally, in the PTI mode, electric energy and mechanical energy, such as that from the engine together transmit power to the propulsion machine by additionally supplying power obtained from a battery or generator to the motor while the engine is running.

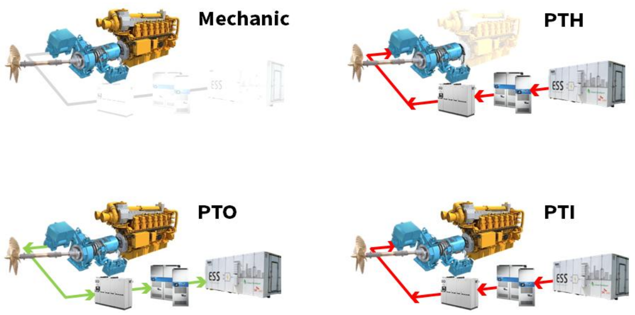

Fig. 4. Operation mode of a diesel–electric hybrid propulsion system.

3.2 Conventional rule–based strategy

In the conventional rule-based strategy, as shown in Fig. 5, first, in the 0–20% section of the full load, only the motor is operated, and then, in the 20–80% of the full load, only the engine is operated depending on the load. Finally, in the 80–100% section of the full load, the engine is operated at 100% output, and the remaining load is supported by the motor. Accordingly, the motor is driven when operating the low-load and high-load sections.

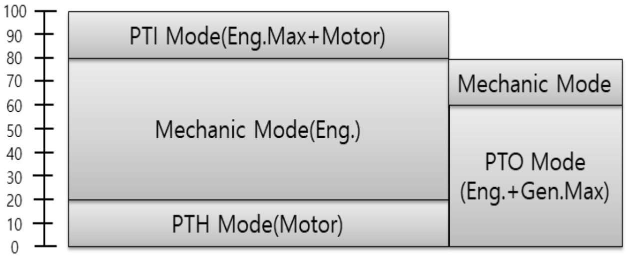

Fig. 5. Conventional rule-based strategy.

3.3 Proposed ECMS

The proposed ECMS allows the engine and motor to operate under optimum fuel efficiency conditions. Therefore, it is controlled to operate as much as possible in the range of 75–80%, which is the optimum efficiency load section of the engine. The strategy to which control is applied uses the motor in the 0–20% section of the full load, as shown in Fig. 6, and operates only the engine in 20–60% section of the full load. In the 60–80% section of the full load, the engine provides a constant output of 75%, which is the optimal efficiency load section, and the motor supports the rest of the load.

Finally, in the 80–100% section of the full load, the motor operates at maximum output, and the engine supports the rest of the load.

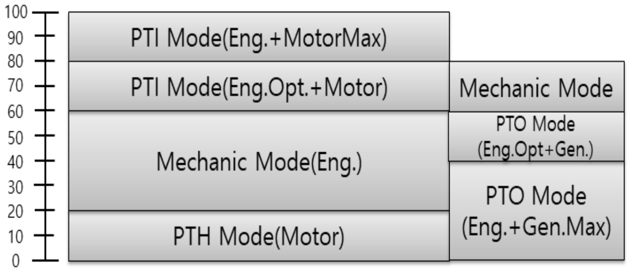

Fig. 6. Proposed ECMS.

4. Simulation

4.1 Target vessel

Yeondeungho, a coastal combined fishing vessel that sails along the coast of Hari Port in Busan, was selected as the target vessel and set based on the load operating environment of the vessel. This is the same as that shown in Fig. 7, and the specifications of the ship are listed in Table 4.

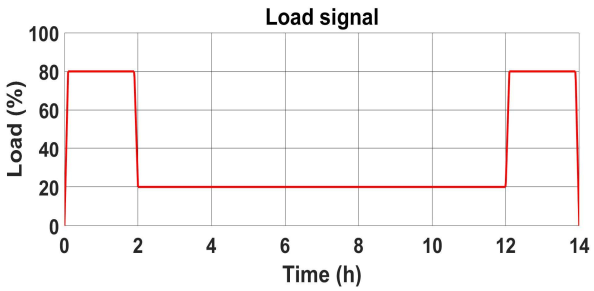

Fig. 7. Load profile of the target fishing boat.

Table 4. Target ship specifications

Target ship specifications	
Rated power	580 [kW]
Gross tonnage	9.77 [ton]
Length	24.5 [m]

4.2 Modeling of diesel–electric hybrid propulsion system

In this study, a diesel - electric hybrid propulsion system was implemented using the MATLAB/SimDrive and SimElectric program, as shown in Fig. 8. The model included a part comprising a battery and shaft generator motor required for propulsion using electric power and another part comprising an engine for propulsion using mechanical force. In addition, it included DC/DC converter, bidirectional power converter, gearbox, and propeller.

4.3 Conventional rule–based strategy

As shown in Fig. 7, a simulation was performed based on the load operating environment of Yeondeungho, a 9.77 t coastal combined fishing vessel. Fig. 9 presents the output of the propeller based on the existing rule-based strategy according to the load operating environment.

The outputs of the engine and motor followed the rule-based strategy, as shown in Figs. 10 - 11. The engine output was 465 kW in the 0 - 2 h and 12 - 14 h sections. In contrast, the output of the motor was zero. In the 2 - 12 h period, the motor operated with an output of 115 kW. When the SOC reached the lowest level of the range, the engine was started, 115 kW of the total 230 kW was used as the propeller output, and the remaining 115 kW was used to charge the battery.

When SOC reached the maximum usage range, the engine was stopped, the motor was started to generate an output of 115 kW, and this EMS was used in this section.

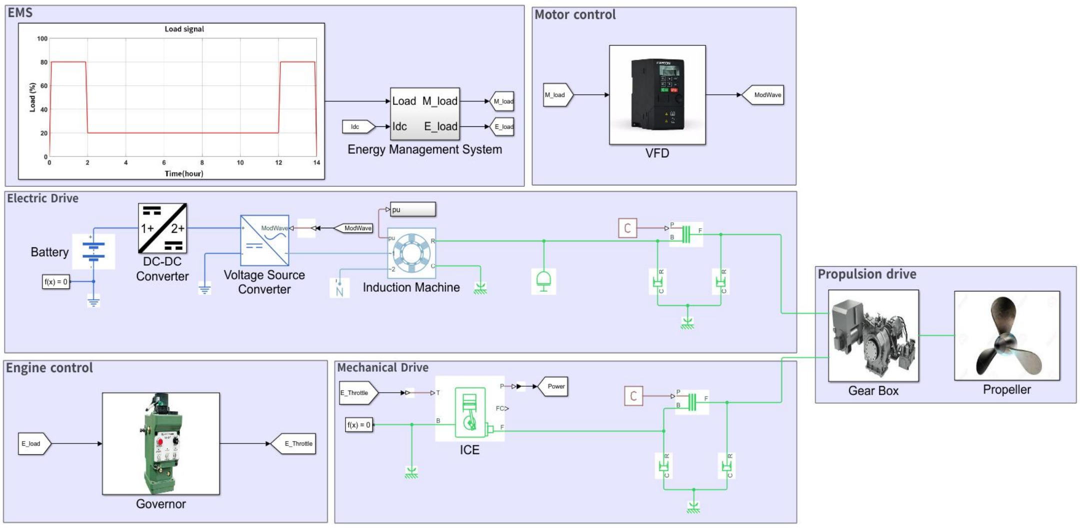

Fig. 8. Simulation modeling of a diesel - electric hybrid propulsion system.

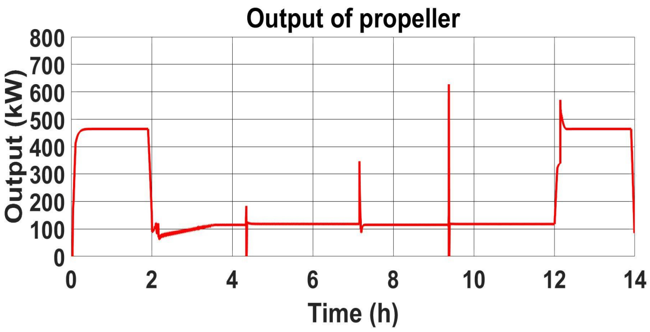

Fig. 9. Simulation results for a conventional output of the propeller.

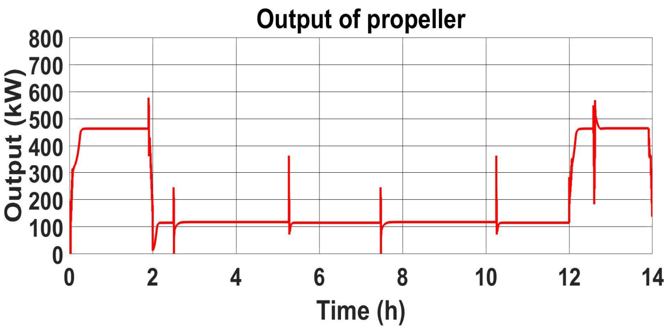

Fig. 12. Simulation results for the proposed output of the propeller.

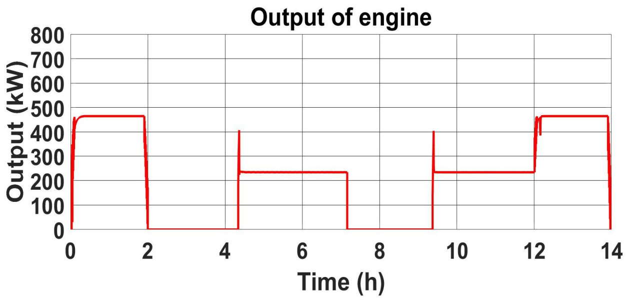

Fig. 10. Simulation results for the output of the engine.

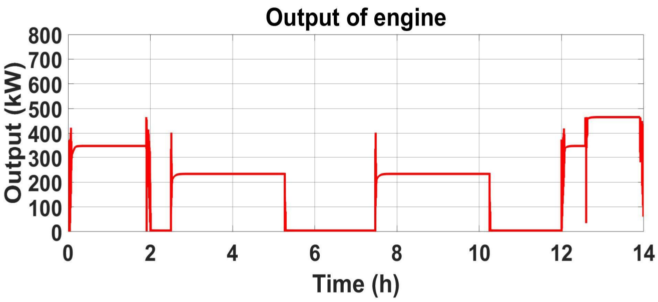

Fig. 13. Simulation results for the output of the engine.

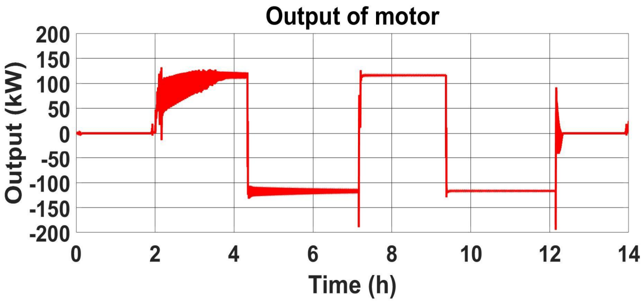

Fig. 11. Simulation results for the output of the motor.

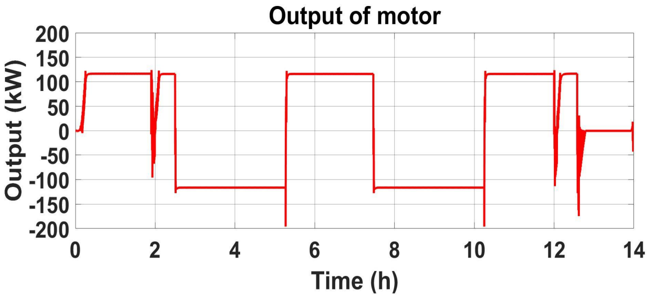

Fig. 14. Simulation results for the output of the motor.

4.4 Proposed ECMS

In the diesel–electric hybrid propulsion system to which the ECMS was applied, as shown in Fig. 12, the output of the propeller followed the same, but the operating section was different owing to the system that controls the engine and motor to achieve the optimum fuel efficiency.

As shown in Figs. 13–14, unlike ships to which the conventional rule-based strategy was applied, the motor started from the beginning and operates in parallel with the engine, and the output of the engine was approximately 350 kW to maintain the optimum fuel consumption section.

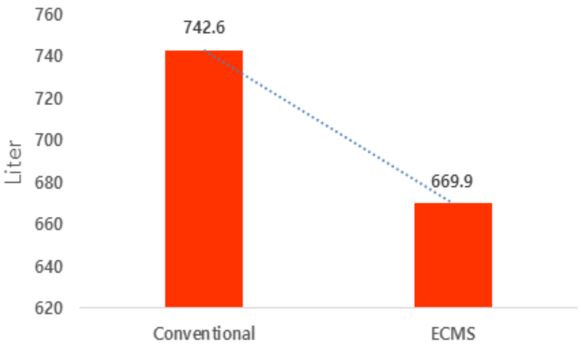

Fig. 15. Comparison of fuel consumption.

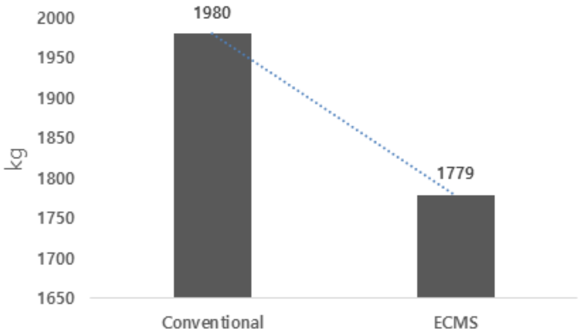

Fig. 16. Comparison of CO2 emissions.

The simulation results indicated that the fuel consumption decreased by 10.2% from 742.61L to 669.91L, as shown in Fig. 15, in the operation mode using the proposed ECMS-applied diesel‑electric hybrid propulsion system compared to the conventional diesel‑electric hybrid propulsion system operated by the rule-based strategy control. The CO2 exhaust gas emissions decreased from 1980 kg to 1779 kg as shown in Fig. 16.

5. Conclusion

Fuel consumption and CO2 exhaust gas emissions were reduced by 10.2% in fishing boats that applied the proposed ECMS. The reason for the decrease in fuel consumption is that the low-load operation of the engine was replaced with the motor operation, and the engine was operated at the optimum point of fuel consumption. In the case of a coastal combined fishing vessel, the main engine runs at a high speed to navigate to the fishing site; the operating time is generally 4 h, and the working time is approximately 10 h. During operation, the main engine is operated at a low load of approximately 20%. The biggest problem with such low-load operation is that it generates a large amount of air-polluting exhaust gas. However, in this study, when the motor was started using a battery, it avoided the low-load operation section of the main engine and maintained the optimum point of fuel consumption, thereby decreasing air pollution. In addition, exhaust gas greatly reduced. When the motor was operated, the explosion sound and vibration generated by combustion in the cylinder of the engine were not generated; thus, the operation was possible with low noise and no vibration.

Currently, this is difficult to apply to small fishing boats owing to the large volume of the battery and the limited space for mounting the battery because the energy density is not high owing to the lack of technology for the battery. To solve this problem, as in this study, an eco-friendly ship can be built by applying a diesel‑electric combined propulsion system (battery + engine), rather than propelling it with batteries alone, and implementing the replacement project for aging government ships or ships that emit air pollution.

In this study, research and simulation were conducted by modeling a complex propulsion system using a battery + propulsion motor and an engine with ECMS control. In the future, we intend to conduct a study on the system design for better fuel consumption and emission reduction by applying other optimal controls to the system for optimal fuel consumption.

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