Development of the Hybrid Tugboat System

SHIRAISHI Koichi : Manager, Marine Engineering Group, Niigata Power Systems Co., Ltd.
MINAMI Syunichi : Principal Engineer, Quality & Environment Issue Department, Niigata Power Systems Co., Ltd.
KODERA Masanori : Electronic and Electrical Technology Group, Niigata Power Systems Co., Ltd.

The main engine of tugboats is designed for high-power propulsion given the relatively small size of a tugboat's hull, but most of their operation time is spent with low loads. In order to improve the performance of such ships, we came to the conclusion that a composite system was needed and developed a hybrid propulsion system. This system consists of an engine and a propulsion system using a motor and lithium ion batteries and it has achieved the fuel consumption and CO_2 emissions reduction target of 20% in comparison with conventional tugboats. The lithium ion batteries can be charged by the power generator and also by plugging in to electric power on land (shore power). In March 2013, Japan's first hybrid tugboat was put into service.

1. Introduction

Niigata Power Systems Co., Ltd. developed Japan's first hybrid propulsion system for tugboats. This system is a propulsion system using an engine as well as a motor and lithium-ion battery, similar to a hybrid vehicle. The system is able to reduce fuel consumption by approximately 20% compared to a conventional system, thereby contributing to a reduced environmental load.

2. Overview of hybrid tugboats

With this hybrid propulsion system, it is possible to reduce inefficiencies in energy usage by selecting from power sources with different characteristics, such as the main engine, lithium-ion battery, diesel generator and motor (an optimal propulsion power source for the operating mode of the tugboat) and adequately controlling the selected propulsion power source. The features of this system are summarized below. In addition, **Fig. 1** illustrates a comparison of a conventional system and the hybrid system.

(1) A Z-type propulsion device (Z-Peller) is integrated with the motor, making the system more compact.

(2) Since there are two sources of driving force (the main engine and a motor/generator) and two sources of electricity (a diesel generator and a lithium-ion battery), even if one power system malfunctions, another power

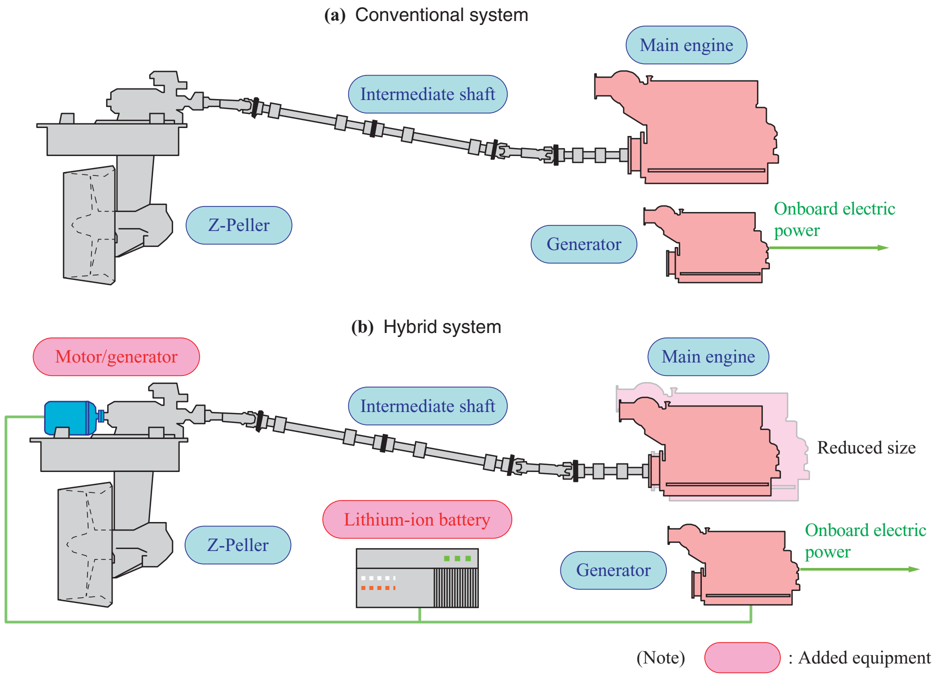

Fig. 1 Comparison of the conventional system and the hybrid system

system can be used, thereby providing redundancy.

(3) The lithium-ion battery is actively used during low-speed operation, and fuel consumption is reduced by stopping the main engine.

(4) The motor can assist the main engine in response to sudden load variations, thereby preventing the momentary emission of black smoke.

The lithium-ion battery to be installed on board the ship requires advanced control of charge/discharge performance, with special care and consideration for safety in use on board a ship. The lithium-ion battery is primarily charged with electricity supplied from the onshore power source (hereinafter, shore power), but can also be supplied with power (charged) from the on-board generator.

3. Operating modes

In this system, different modes are used depending on the type of operation. The system includes two modes: a "transit mode" used during transit, and a "working mode" used during bollared-pull (working).

Figure 2 illustrates a general operating data model of harbor tugboats. "Transit mode" is selected for going to or returning from the workpoint, while "working mode" is selected for departure or arrival navigation of large ships in the harbor. A mode control switch is provided on a console on the bridge of the tugboat, and the operating mode is switched at the captain's discretion.

First, the relationship between the propeller speed of the propulsion device and the propeller output in "transit mode" is illustrated in **Fig. 3**.

In the motor propulsion region where the propeller speed of the propulsion device is less than or equal to a set speed, a built-in clutch in the Z-Peller is disengaged, the speed of the motor/generator is controlled, and the tugboat is propelled by the propeller which is being driven by the motor/generator (**Fig. 4**).

Next, the relationship between the propeller speed of the propulsion device and the propeller output in "work mode" is illustrated in **Fig. 5**. In the idle to constant speed range, the

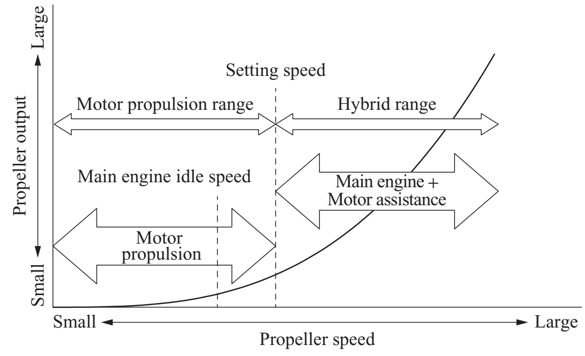

Fig. 3 Transit mode

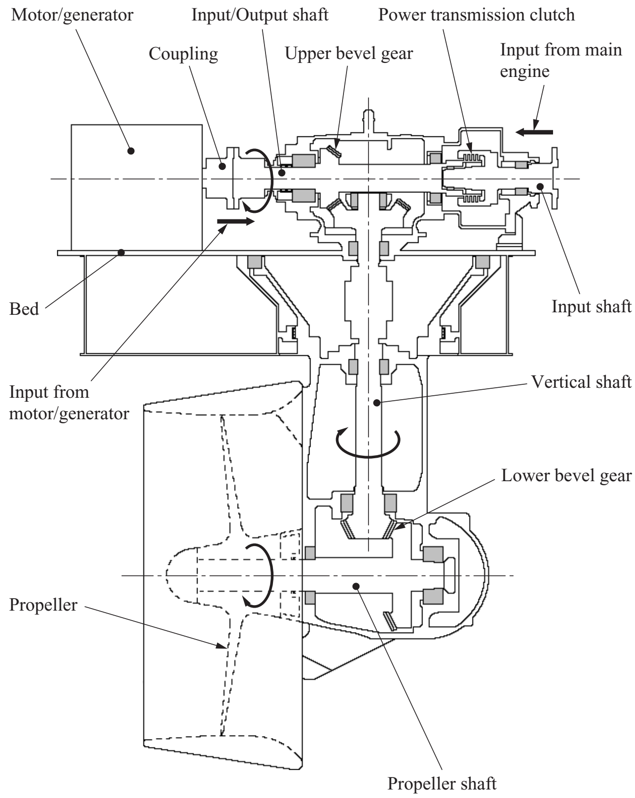

Fig. 4 Z type propulsion (with motor/generator)

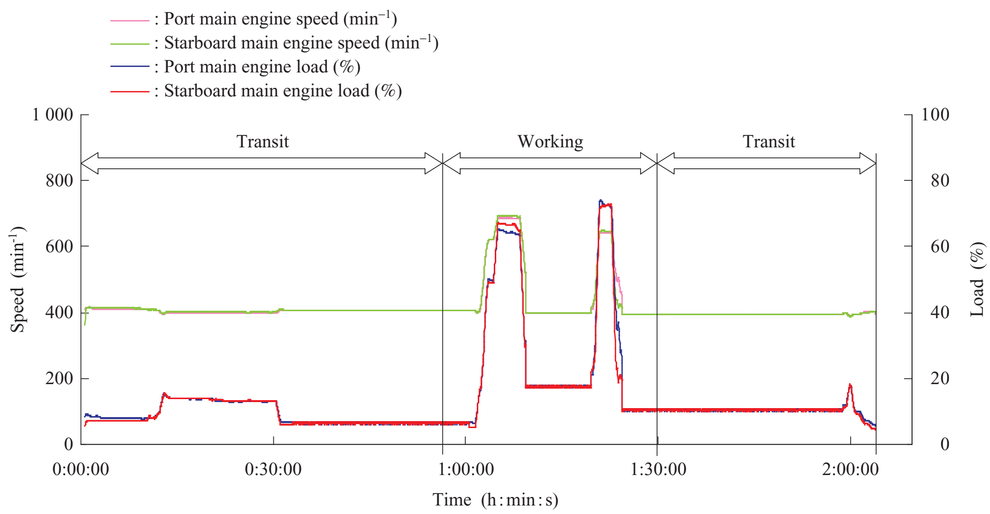

Fig. 2 General operating data of harbor tugboats

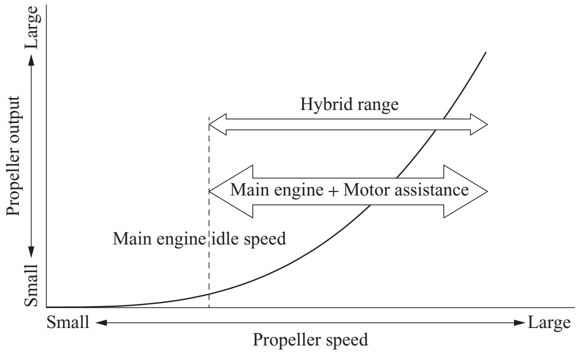

Fig. 5 Work mode (Bollard-Pull mode)

tugboat is driven by the main engine, and above the "Engine idle speed" torque is assisted by the motor/generator.

4. Operation

Ship operation will be explained by "transmit mode" and "working mode." **Figure 6** illustrates the operating modes in each state, and illustrates the electrical system when the tugboat is berthed, in transit, and doing work, on the basis of a schematic plan view of a harbor.

When berthed, the lithium-ion battery is charged from shore power. When fully charged, the tugboat departs. In "transit mode," switching from the low load (low speed) system to the high load (high speed) system is automatic as the throttle handle is raised. Note that the switch from "transit mode" to "working mode" is made manually by the captain while the tugboat is in the ③⇔④ position illustrated in **Fig. 6-(a)**.

5. Simulation

In order to confirm the configuration and advantages of the hybrid system, an investigation was conducted by setting the propulsion output to 4 400 PS (3 236 kW) with two shafts.

The operating data model illustrated in **Fig. 3** was created from actual operating data. In order to confirm the advantages of the hybrid system, simulations were conducted to check the differences in fuel consumption and CO_2 emissions during operation between a conventional tugboat and the hybrid tugboat. **Figure 7** illustrates a comparison of the fuel consumption rates obtained from each simulation, with the total consumption rate of the conventional tugboat normalized to 100%.

During operation of the hybrid system, when operating at low speed, propulsion is obtained from the motor driven by electric power from the lithium-ion battery. During this period, the main engine is shut down, which is effective at reducing factors such as the fuel consumption rate.

From the simulation results, it was confirmed that the hybrid system results in a 25% reduction in fuel consumption and a 25% reduction in CO_2 emissions compared to the conventional system, thereby achieving the target of a 20% reduction in fuel consumption and a 20% reduction in CO_2 emissions.

6. Design of hybrid tugboats

The size of the hybrid tugboat was made to be the same as a conventional tugboat.

The main engine capacity, battery capacity, and motor/generator capacity that strike an optimal balance between environmental performance, economic efficiency, and actual operation were decided based on simulations involving various conditions seen during actual operation as well as on the investigation into how the layout inside the tugboat should be. With regard to the installation of hybrid equipment, various safety measures were desired. One of which was a remote monitoring system that was implemented to enable the transmission of an emergency warning to a supervisor on land. As a result, it is possible to monitor the state of the hybrid equipment from the shore.

Although the hybrid system requires more equipment than a conventional system, all pieces of equipment were successfully installed by optimizing the on-board equipment layout. **Figure 8** illustrates the schematic layout and capacity of the hybrid tugboat.

7. Lithium-ion battery

In Japan, there are few prior examples of applying lithium-ion batteries for use onboard ships. Thus, in order to ensure safety, it was desirable to use lithium-ion batteries with safer designs.

This system adopts an IHI (A123 Systems) lithium-ion battery with lithium iron phosphate ($LiFePO_4$) as the electrode material. Since $LiFePO_4$ is used for the anode, oxygen separation and thermal runaway are unlikely to occur even at high temperatures caused by heat produced due to internal shorting. For this reason, the risk of fire or explosion is extremely low.

To ensure safety, safety testing was conducted primarily on the basis of the SBA standard (Battery Association of Japan), and the hybrid system was confirmed to be sufficiently safe.

Note that in this hybrid system, the battery system, including the voltage regulators (DC/DC converters) and Battery Control Unit (BCU), are made by IHI (**Fig. 9**).

8. The hybrid tugboat in service

From the results obtained in the development described above, it was confirmed that the hybrid system is greatly effective at reducing the environmental load. To confirm this advantage, construction of a hybrid tugboat was commenced, and in March 2013, the hybrid tugboat entered service in Yokohama Harbor as the tugboat "TSUBASA" (256 tons) managed by the Wing Maritime Service Corporation of the Nippon Yusen Kabushiki Kaisha Group. This is the first time that a hybrid tugboat equipped with a plugin function enabling charging from land has entered into service in Japan (**Figs. 10** and **11**).

This newly commissioned hybrid tugboat is equipped with a motor/generator and lithium-ion battery in addition to a conventional diesel engine, and is capable of a top speed of 15 kn (approx. 28 km/h), or 10 kn (approx. 19 km/h) when

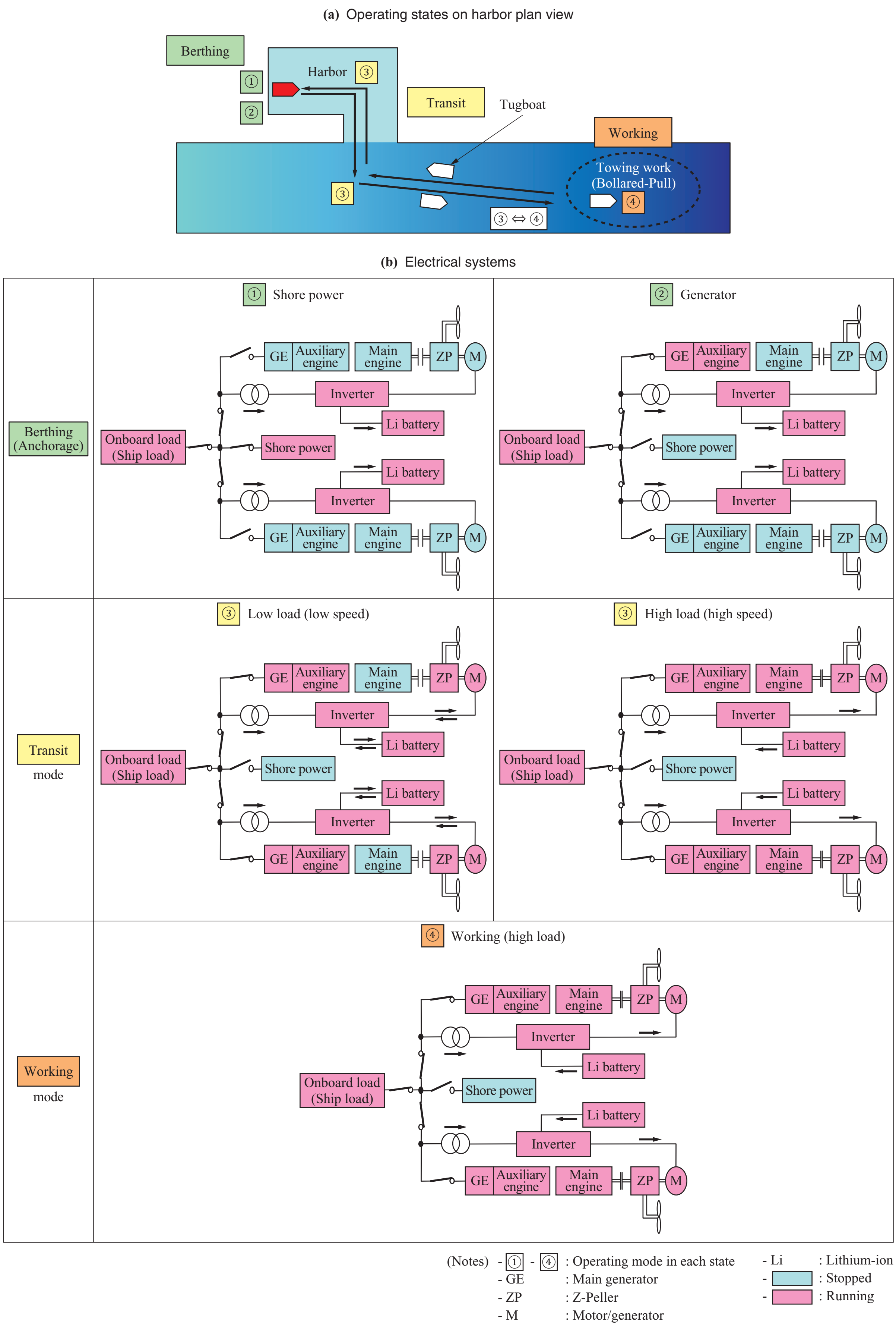

Fig. 6 Operating modes

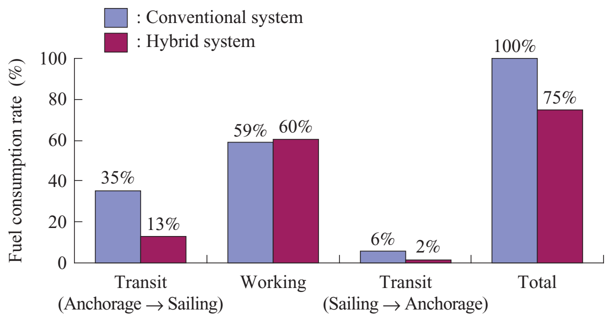

Fig. 7 Simulation results (fuel consumption rate)

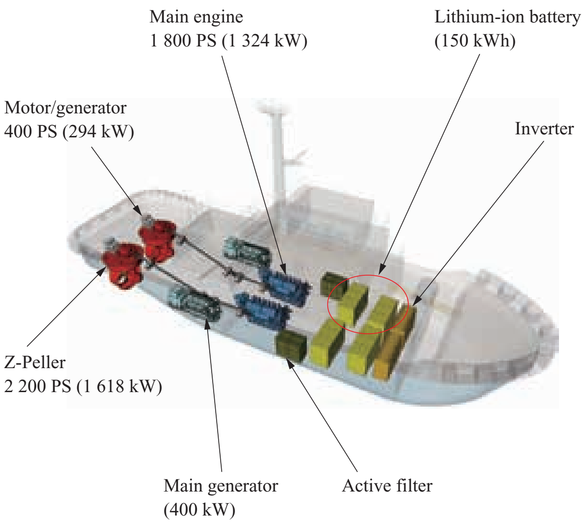

Fig. 8 Layout and capacity of the hybrid tugboat

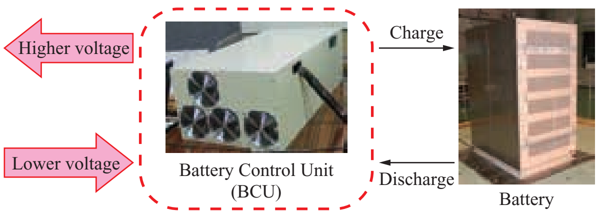

Fig. 9 Lithium ion battery

Fig. 10 Hybrid tugboat "TSUBASA"

Fig. 11 "Hybrid" Logo

driven by the motor/generator. The lithium-ion battery can be charged by the generator onboard the tugboat, in addition to being charged from power supply facilities installed in the berthing quay wall.

The major specifications of the hybrid tugboat are listed below.

Length overall (Loa)	37.20 m
Breadth (B)	9.80 m
Depth (D)	4.40 m
Draft	3.35 m
Tonnage	256 tons
Class	JG (Maritime Bureau of Japan)
Plying limit	Coastal (limited)
Speed	15.0 kn
Bollard pull	
Ahead	55 t
Astern	52 t
Main engine	Niigata 6L28HX × 2
	1 324 kW × 2
Motor/generator	294 kW × 2
Propeller	Niigata ZP-31 × 2
Lithium-ion battery	IHI (A123 Systems)
	150 kWh × 2

9. Conclusion

After the hybrid tugboat "TSUBASA" entered service, operating data was collected, and it was confirmed that the advantages indicated by the simulation are also obtained in practice.

According to the collected data, reductions in excess of the target 20% reduction in fuel consumption and 20% reduction in CO_2 emissions were obtained. In the future, we will continue to collect operating data, investigate optimal operating methods, and attempt further reductions in fuel consumption and CO_2 emissions.

The developed hybrid propulsion system was developed with the initial intent of applying the system to tugboats, but given the above features, the hybrid propulsion system is also applicable to vessels other than tugboats, such as supply boats, small ferries, and sightseeing ships, for example. The hybrid propulsion system includes multiple power sources, and by optimizing the capacity and control of the motor, lithium-ion battery, main engine, and diesel generator to combine according to the required operating conditions of the vessel, the hybrid propulsion system can be applied to a variety of usage scenarios.

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