Development of a Power Management System of a Fuel cell-Battery-Solar cell Hybrid Ferry

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ABSTRACT

Due to the International Maritime Organization's efforts to enact strict regulations and strategic plans to gradually reduce greenhouse gas emissions and eliminate them from the shipping industry as soon as possible within the next century, all-electric ships have become more and more noticeable. It is crucial to use an electric propulsion system in place of the current mechanical one. In this research study, the development of a power management system for a fuel cell-battery-solar cell hybrid ferry is presented, and system performance and stability are examined. Under dynamic ferry load conditions, the system performance is examined. The outcomes of each system's simulation show how each system can operate successfully in a hybrid configuration while carrying out the necessary prescribed functions. In spite of the system's dynamic and transient situations, the overall system performance implies stable system functioning where the system parameters vary within acceptable bounds.

1. Introduction

Shipping has grown rapidly in recent years and will eventually be a major source of CO_2, NO_X, and SO_X emissions. In response, the International Maritime Organization (IMO) imposed mandatory energy-efficiency measures on ships in order to reduce emissions of greenhouse gases (GHGs). Further, the IMO has developed an initial strategic plan aimed at reducing GHG emissions systematically. By 2050, the goal is to reduce international shipping's GHG emissions by 50% versus 2008 and to reduce carbon intensity by 40% in 2030 and 70% in 2050, thereby phasing out GHG emissions as soon as possible within this century[1-3]. Ship owners and builders already focus on various technologies and creative solutions to reduce ship emissions in order to meet IMO regulations, which are mandated to become more challenging as time goes on. This will result in new ships being 30% more energy-efficient by 2025 than those built in 2014[3].

Power electronics technologies have accelerated ship transformation toward all-electric ships (AESs)[4], enabling the integration of alternative zero-emission power sources, renewable energy sources, and energy storage systems into marine power systems with their integrated power system feature, launching hybrid electric ships. AESs are notable for their ship design, continuous operating efficiency[5], and fuel consumption reduction[6].

Zero-emission power sources for marine propulsion and auxiliary loads are needed immediately to reduce emissions and move toward sustainable transport. Fuel cells using hydrogen fuels are the most viable alternative to marine fossil fuels after years of technological growth. Fuel cells cannot power high-power vessels because of their low power capabilities. Thus, coastal ferries use fuel cell systems with hybrid power systems and batteries. Fuel cells perform poorly for transient power needs, so it follows steady-state power demands. The battery system handles power fluctuations.

This research focuses on developing a power management system for a fuel cell-battery-solar cell hybrid ferry and examining its performance under a dynamic load profile. Managing fuel cell and battery power is critical. Dynamic operation relies on battery power, while steady-state power is provided by the fuel cell being the primary power source. PV energy charges batteries whenever feasible. The polymer electrolyte membrane fuel cell (PEMFC) fuel cell module and lithium-ion battery system are utilized.

2. System Modeling

2.1 System Architecture

For this research study, the standard DC bus approach is employed as shown in Fig. 1. In the fuel cell, battery, and solar cell systems, the required DC-DC converters are employed independently to boost the input voltages and execute the desired individual system control actions. The vessel load is then connected via a voltage source inverter (VSI), generating the appropriate AC voltage source for the vessel load.

The fuel cell-battery-solar cell hybrid power system is modeled using the MATLAB Simulink application. Each system is modeled in conjunction with the appropriate control systems. In the hybrid power system, the fuel cell system with a 500 kW capacity is the primary source of power under steady-state conditions. Due to the fact that the fuel cell system is extremely load-sensitive, the fuel cell voltage varies with cell current. In order to obtain stable performance from the fuel cell system, a constant power operation of 300 kW is maintained throughout system load operation. The 250 kW battery system serves as the secondary power source for the hybrid power system. It is employed to operate in dynamic conditions by switching between charging and discharging states of operation during system variable load operations. Controlling the charging and discharging modes of the battery system enables the system to operate in zero, static, or dynamic solar power conditions. The 15 kW solar cell system is used to allow for the hybrid operation with the battery system and charge the battery continuously during the vessel run time. Hence, the overall system must satisfy the power balance condition as given in Eq. 1, where P_L is vessel load

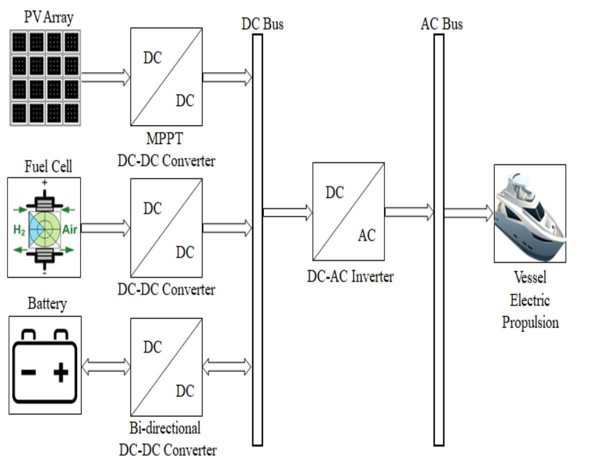

Fig.1 Fuel cell-battery-solar cell hybrid power system architecture - Common DC bus

power, P_{FC} is fuel cell power, P_{Bat} is battery power and P_{PV} is PV power.

$$P_L = P_{FC} + P_{Bat} + P_{PV} \tag{1}$$

2.2 Power Management System

The power management system is required for each system to accomplish stated functions while optimizing each system operation at corresponding load conditions via continuous system monitoring. The flow diagram of the power management system is illustrated in Fig. 2. The system module parameters are presented in Table 1.

3. Simulation Results and Discussion

A short-term dynamic propulsion load profile as shown in Fig. 3 is employed to investigate the power management system performance of the Fuel cell-battery-solar cell hybrid Ferry.

For vessel AC load operations, it is necessary that the 3-phase voltage VSI with its controller generates a 3-phase AC voltage of 440 Vrms and a frequency of 60 Hz. As illustrated in Fig. 4, the input DC bus voltage to the VSI is set to 1000 V, which is continually controlled by the battery or fuel cell systems. As the fuel cell system controller controls the DC bus voltage, the modulation index of the inverter controller, as shown in Fig. 5, is steadily adjusted to provide the appropriate AC voltage.

The root mean square (RMS) line voltage and frequency characteristics of the 3-phase AC voltage are illustrated in Fig. 6 and 7. After the system reaches steady-state performance, the RMS line voltage continuously maintains at 440 V, which occurs throughout the system operation. The frequency of the AC system varies around 60 Hz, and the variation is almost steady.

Fig. 8 shows the overall system power flow under dynamic load conditions and the battery system continuously charges from the fuel cell power at low load conditions until 300 kW. Then, the battery system and the fuel cell system are jointly serving the vessel high load conditions. This operation continues throughout the vessel continuous dynamic load conditions.

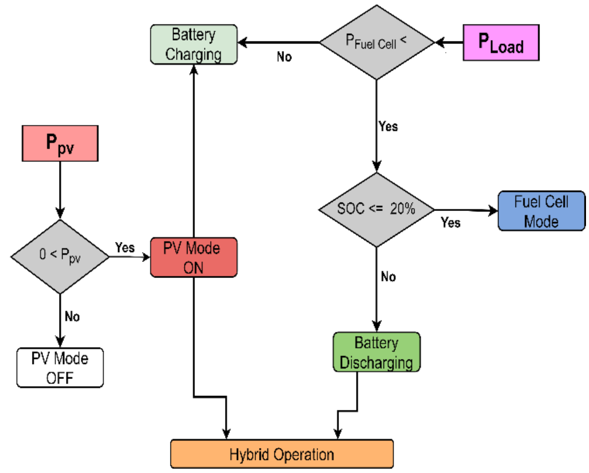

Fig.2 Power management system flow diagram

Table 1 System module parameters

System	Capacity
Fuel Cell (kW)	500
Battery (kW/kWh)	250/540
Solar Cell (kW)	15
3-phase VSI Inverter (kW)	500
DC Bus Voltage (V)	1000
Vessel AC Load (V_{rms})	440
Frequency (Hz)	60

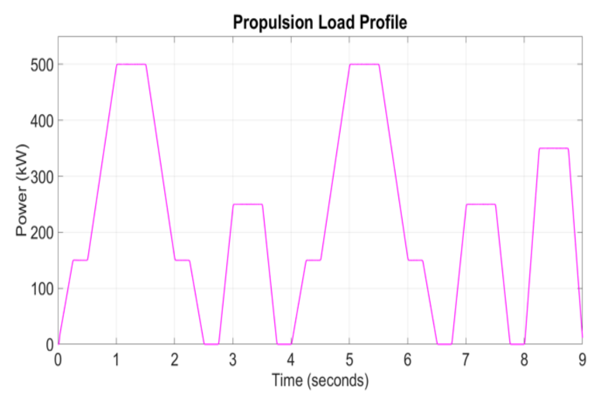

Fig.3 Propulsion load profile

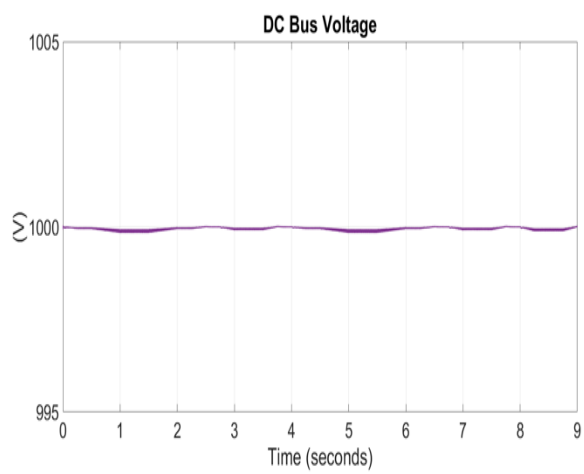

Fig.4 DC bus voltage characteristic

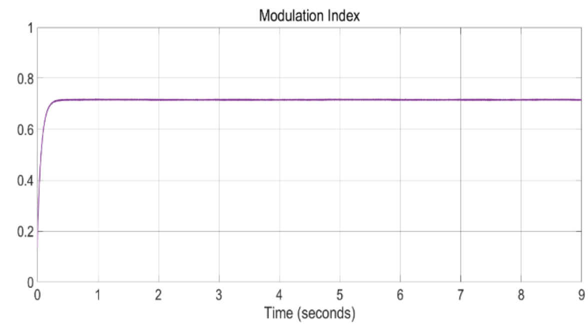

Fig.5 Modulation index of the VSI

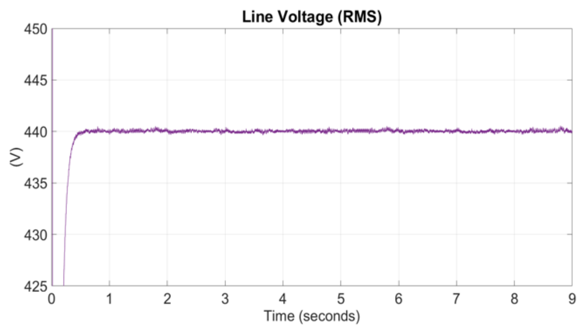

Fig.6 Line voltage (RMS) characteristic of inverter generated AC voltage

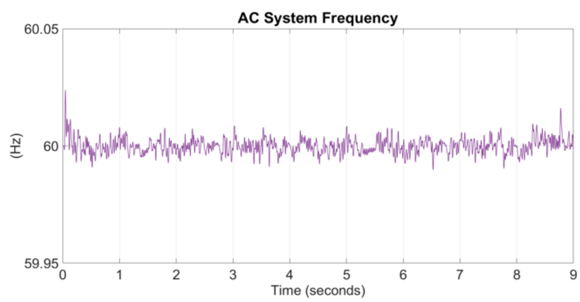

Fig.7 Frequency characteristic of inverter generated AC voltage

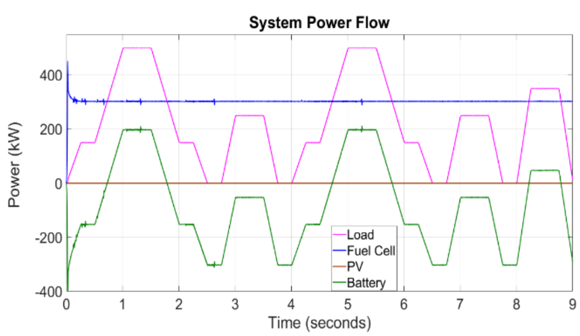

Fig.8 Overall system power flow under zero solar power conditions

4. Conclusion

This study presented the development of a power management system for a fuel cell-battery-solar cell hybrid ferry. The primary goal of this study was to investigate system performance in which the fuel cell system is used as the primary power source to deliver steady-state power continuously, and the battery system is used as the secondary power source to support the fuel cell system when diving high vessel loads. To charge the battery system from solar power, the solar cell system is incorporated with the battery system in a hybrid design. The VSI control system converts the DC input power to alternating current while creating the required alternating current side voltage for the vessel loads. The power management control system enables the battery charging mode to charge the battery system from surplus fuel cell power below the vessel load condition of 300 kW and the discharging mode above 300 kW as the dynamic vessel load varies from 0-500 kW with different steady-state conditions at 150 kW, 250 kW, 350 kW, and 500 kW. The implemented hybrid system improves system performance by appropriately executing stated system controls. Regardless of the system dynamics and transients, system parameters such as DC bus voltage and inverter-generated AC parameters vary within permissible limits, indicating the overall system's stability and reliability.

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