Journal of
*Marine Science and Engineering*

MDPI

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# Development of Hardware-in-the-Loop Simulation Test Bed to Verify and Validate Power Management System for LNG Carriers

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**Abstract:** Liquefied natural gas carrier (LNGC) orders are increasing owing to marine environment regulations. The complexity of the integrated system applied to shipbuilding and software errors have increased with the high degree of automation. Direct on-site inspection methods are associated with high costs and safety risks, whereas software-based simulations rely heavily on the accuracy of the models of power system components. Hardware-in-the-loop simulation (HILS) can be utilized for designing and testing intricate real-time embedded systems. Specifically, HILS offers a reliable means of evaluating power management system (PMS) performance for LNGCs, which are high-value vessels commonly used in offshore plants. This study proposes a PMS–HIL test bed comprising a power supply unit, consumer, simulation control console, and main switchboard. The proposed HILS test bed utilizes the real equipment data of the shipbuilding industry to replicate the conditions associated with actual LNGCs. The proposed system is verified and validated through a software acceptance test procedure. Additionally, load-sharing, load-dependent start, blackout prevention, and preferential tests are performed for the PMS function evaluation. Test results indicate that the proposed system has great potential for conventional PMS commissioning. Therefore, it exhibits the potential to replace traditional factory acceptance tests. Additional development of the system will be conducted for ship automation, utilizing PMS control and an energy management system.

**Keywords:** liquefied natural gas carrier (LNGC); power management system (PMS); hardware-in-the-loop (HIL); modeling and simulation (M&S); test bed



**Citation:** Lee, K. Development of Hardware-in-the-Loop Simulation Test Bed to Verify and Validate Power Management System for LNG Carriers. *J. Mar. Sci. Eng.* **2024**, *12*, 1236. https://doi.org/10.3390/jmse12071236

Academic Editors: Jian Li, Guangdong Zhou and Songhan Zhang

Received: 3 June 2024
Revised: 3 July 2024
Accepted: 11 July 2024
Published: 22 July 2024



## 1. Introduction

Eco-friendly vessels and autonomous vessels have garnered increasing attention in the shipbuilding industry. In particular, in the merchant marine sector, high-value-added vessels, such as liquefied natural gas carriers (LNGCs), shuttle tankers, drillships, and offshore plants, have undergone various changes to fulfill the increasing demands of owners for automation, as depicted in Figure 1 [1]. Among the different high-value-added vessels, LNGC orders are projected to markedly increase in the future owing to marine environment regulations.

The complexity of the integrated systems applied to shipbuilding has increased with automation, which has been accompanied by a rise in software-related errors. Ship and offshore plant integration system software are predicted to become more complex, and there are increasing costs for final testing and debugging by in situ marine commissioning. Therefore, a verification system is required to determine the failure and malfunction of the integrated system. The "DP station keeping incidents" report published by the International Marine Contractors Association reveals that 56 accidents involving dynamic positioning (DP) occurred in 41 vessels. The accidents were primarily caused by electrical errors (21%), computer errors (11%), and power problems (9%). Thus, the safety and reliability of complex control systems in marine and offshore plants are major aspects to consider [2,3].

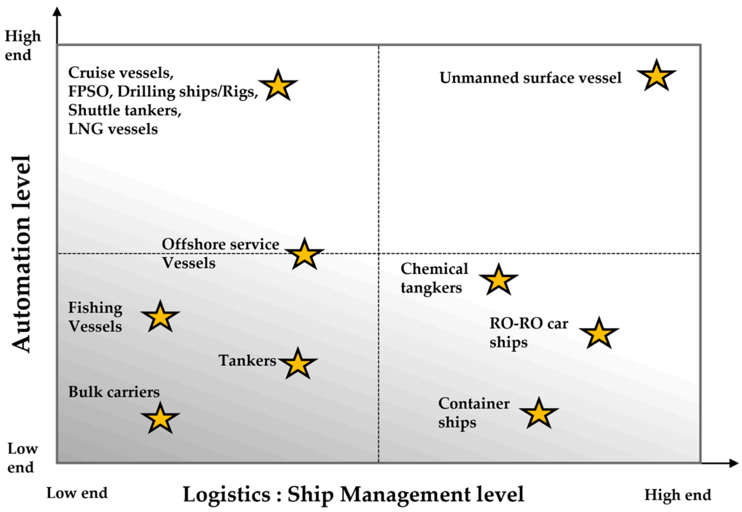


**Figure 1.** Low-end and high-end market segments within ship automation and management levels [1].

Software in-the-loop simulation (SILS) and hardware in-the-loop simulation (HILS), which are software and hardware test validation systems, have improved the reliability of integrated systems in high-value-added ships and offshore plants. The American Bureau of Shipping (ABS) and Det Norske Veritas (DNV) provide verification processes and guidelines for the development of software-based systems for ship or offshore projects and for the integration of each system [4,5]. HILS is a simulation technique for developing or testing a complex real-time system. Additionally, HILS offers a means to validate the control status of the test object and for the complex object to be controlled to assess the functionality of the test object using a dynamic system model for testing and development purposes.

The development stages to ensure the reliability of the software according to integrated software-dependent system (ISDS) [4] and integrated software quality management (ISQM) [5] are shown in Figure 2. In step one, the shipyard and ship owner select the program quantitative management plan (PQMP), confidence level, operation scenario, and reliability availability maintainability and safety (RAMS) criteria. The vendor that supplies each system based on the documents established in stage one establishes the PQMP for the software management and describes the functions of each software system in the functional decomposition diagram (FDD) and technical description (TD). The operating procedures of each system are performed as a use case in accordance with the operation scenario. The FDD/TD use case becomes the main document in the software implementation.

Software coding and internal testing are performed in accordance with the PQMP of the yard and tracing matrix as determined by the ship owner and independent verifier, and verification is completed up to the hardware factory acceptance test (FAT) stage. Software verification is performed through the SW FAT or HIL simulation in the software acceptance test (SAT) once the software implementation is complete. When the software is verified through the HIL simulation, the normal mode function, failure mode function, and scenario-based software test are performed, as illustrated in Figure 2. When the shipbuilder, namely, the system integrator (SI), intends to perform the software verification of the integrated control system in the verification and validation (V&V) process, the software code must perform the verification in an open environment. Considering the constraints of the test environment mentioned above, the HIL simulation is safe and efficient in terms of software verification owing to the nature of the software [6,7].

A simulation test involving multiple scenarios is necessary for successful system integration and safe operation owing to the growing risks associated with constructing LNG vessels. Altosole et al. developed a collaborative simulator to demonstrate the influence of each component on the propulsion plant performance decay; it aims to provide guidance for the proper management and maintenance scheduling of the vessel [8]. Mrzljak et al. presented an energy analysis of the main propulsion steam turbine of an LNGC [9].

Balin et al. proposed a hybrid method for engine failure evaluation to decrease the rates of failures [10]. The role of the energy management system (EMS), which regulates electrical consumption and fuel consumption, is crucial for the operation of LNGCs.

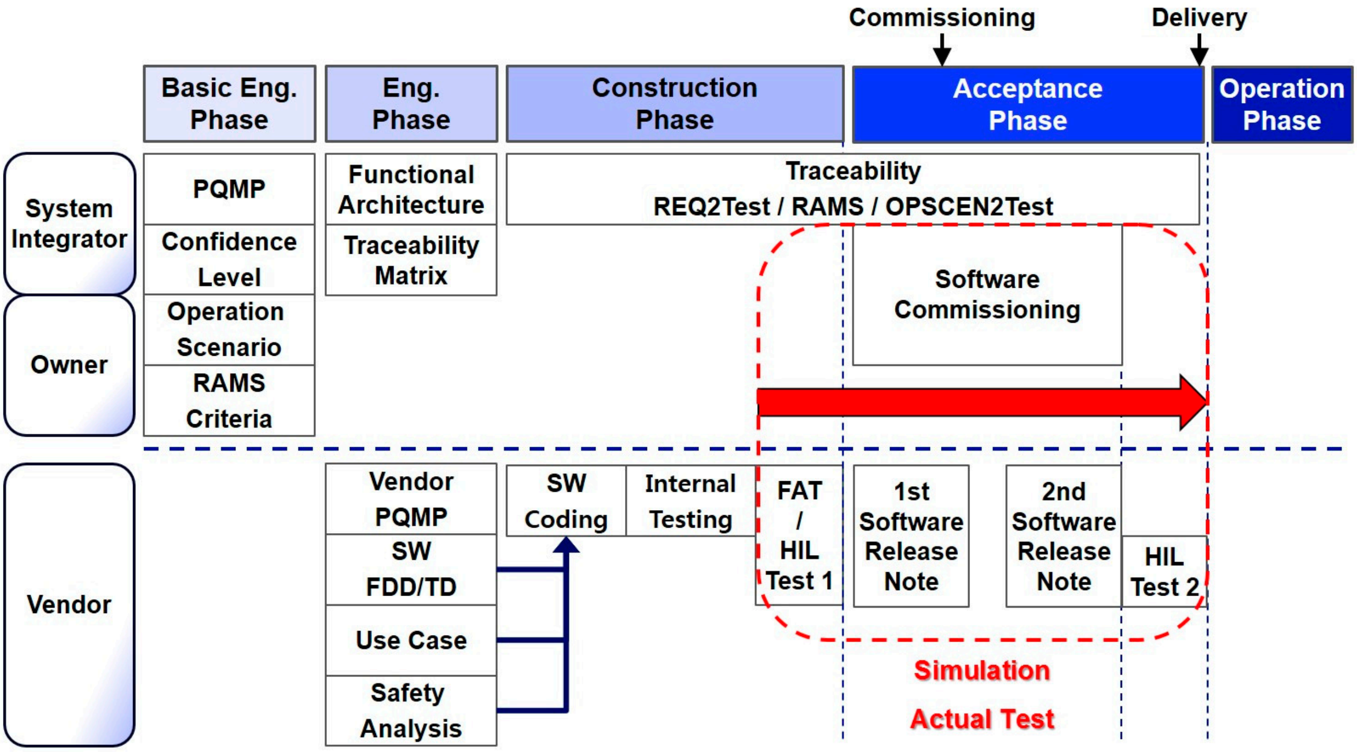


**Figure 2.** Software quality assurance process with the hardware-in-the-loop test.

In LNGCs, the power management system (PMS) is a core component. The PMS operates intricately with energy control systems to optimize performance and safety. The PMS regulates the voltage and frequency of the system while producing real and reactive power [11]. Last, but not least, the PMS averts disruptions in the production and utilization of energy. A malfunctioning PMS system can cause safety hazards, production delays, and potentially catastrophic accidents. Scholars have studied electrical power control systems to avert the aforementioned problems [12,13].

Various approaches have been suggested to assess the performance of the PMS, including direct on-site inspection and indirect software-based simulation. The direct verification method involves assessing the operation of the PMS by utilizing an analog or digital device in a real-world scenario. Despite its usefulness, direct verification is costly and associated with many risks. Moreover, software simulations that rely on the accuracy of power system component models lack the flexibility of actual hardware testing in setting up a complex power system [14,15].

Two key technologies are required to ensure the accuracy and stability of the HILS test bed. One is to model the system components, and the other is to interface the real-time digital simulator (RTDS) with the hardware under test (HUT). Jing et al. and Bouscayrol, et al. detailed the modeling process for various systems, including generators, batteries, and induction machines [16,17]. The interface between the RTDS and HUT is dependent on the device being tested. Moreover, the algorithm for the interface between the power system and electronic load has been described [18,19]. In the controller HILS (CHILS) test, which evaluates the controller, the communication interface is crucial for wind turbine and electric vehicle systems [17,20]. The following is a case study of microgrid validation using an HIL simulation interface. This study verified the impact of a lab-scale microgrid subjected to a cyberattack through fault data injection (FDI) and verified the resilience of the microgrid under various scenarios. The proposed system detected cyberattacks on wind/photovoltaic microgrids through an artificial intelligence (AI)-based fault data injection and evaluated the performance of the smart microgrid to protect against malicious attacks using a remedial action scheme (RAS) [21].

HILS has the potential to improve the quality and reliability of hardware and software testing. HILS reduces the costs and time associated with verifying problems, such as control system failures, incorrect function parameter calculations, and system errors, that adhere to specific regulations. The simulation can test, verify, evaluate, develop, and diagnose malfunctions in electronic equipment [22–24]. However, domestic shipbuilding companies cannot perform the verifications owing to a lack of resources, forcing them to seek guidance from overseas evaluation agencies and research institutes [25,26].

We developed a HILS system for marine equipment that enables the real-time evaluation of the PMS in an LNG vessel. The core components of the ship, including two turbine generators (TGs), a diesel generator (DG), and a governor for the power supply model, are designed using the MathWorks' applications for the HILS testing. The power consumer model comprises thrusters, pumps, and lumped loads, which are common in LNG vessels. The National Instrument PXI employs LabVIEW programming to model the core components, thereby streamlining the HIL testing process. The proposed methodology incorporates a simulation control console (SCC) and an on-board main switchboard (MSBD) to create a realistic shipboard environment, which distinguishes this work from previous studies. An approach is developed to enable bidirectional communication between the SCC and MSBD using open platform communication (OPC) server/client technology and Ethernet communication. The method was implemented on a HILS to provide a convenient monitoring system. The system was verified and validated through a series of tests, including load-sharing, load-dependent start, blackout, and preferential trip tests, using the proposed HIL test bed to evaluate the functions of the PMS.

## 2. Concepts and Methods

### *2.1. Vessel's Power Management System*

The concept of the power management system has been utilized to describe the processes for controlling the automatic operation of electrical generators and alternators to satisfy the current electrical load demands. The concept has been applied to a broad range of control systems, among them, energy management systems [25]. Modern on-board power systems may have an alternative energy source by using multi-fuels, more complex configurations, and occasionally including energy management, exhaust gas treatment, or a combination of these [27].

The programmable logic controller (PLC), commonly referred to as the PMS, manages main switchboards, generators, governors, transformers, circuit breakers, and distribution feeder lines [28]. The PMS regulates the normal operations required to balance power generation and consumption for a diesel generator (DG) and two turbine generators (TGs). The control system communicates with the high-voltage (HV) main switchboards and low-voltage (LV) switchboards via hardwire or fiber optic and Ethernet cables [22].

Power can be supplied to the load more securely while ensuring safety through automatic programming and automatic measurement and the reduction in management manpower to control the power generated by a generator inside a ship equipped with a marine automation system. The PMS is a part of the integrated automation system and is suitable for marine vessels or offshore structures, such as LNGCs, with more than 5000 input/output channels, primarily because the PMS can control and monitor a power system remotely. This feature fulfills the diverse demands of ship owners and is suitable for marine vessels, where software errors caused by marine environmental factors increase as the complexity of the integrated system increases.

The automatic voltage regulator (AVR) adjusts the excitation field current by controlling the voltage level, while the governor adjusts the speed of the diesel engine to regulate the frequency and phase. When the voltage level, frequency, and phase of the standby generator are in sync with those of the target generator, the synchronized generator connects to the running network via the switchboard [26].

A power outage on a vessel can be dire, as it results in the failure of the propulsion and dynamic positioning systems. It is a common occurrence when the power required by the load exceeds the generator capacity. Therefore, the PMS is required to monitor power consumption and generation [23,26].

The PMS is tested in a simulation, connected to a simulator, and simulated with HILS. This feature can significantly reduce the cost of ship development and commissioning by identifying problems in the design phase, such as checking the sequence operation of the power system, parameter setting, alarm indication, and system error.

### *2.2. Hardware-in-the-Loop Simulation (HILS) for LNGC*

HILS is a widely used method for the development and testing of complex real-time embedded systems. It offers a highly effective platform by incorporating the dynamics of the system being tested into the test environment, which is accomplished by adding a mathematical representation of all relevant systems [6]. A key advantage of HILS is its high level of customization, which makes it applicable to a wide range of embedded systems in various industries, including vehicles, aircraft, ships, offshore facilities, and more [7]. Figure 3 shows the PMS-HIL simulator architecture for LNG carriers. It comprises PMS units, power suppliers, power consumers, and process control network. Generally, a HILS that employs various components must implement equipment simulation and simulation control.

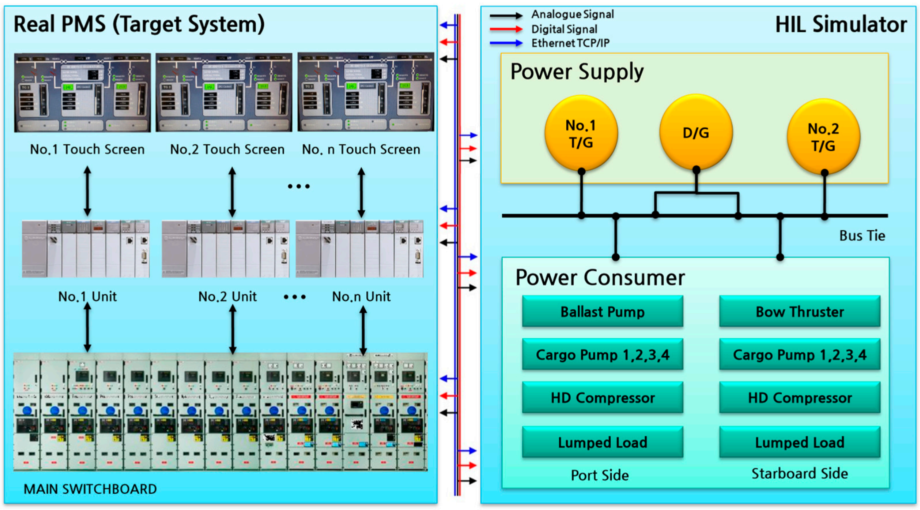


**Figure 3.** HIL simulator and target system concept for LNGC-PMS.

The development and testing of intricate real-time embedded systems use HILS devices. The operation of a HILS device is very similar to that of a HILS, i.e., it involves substituting a computer simulation for the actual device in the mechanism of the control system to perform operational verification. In the shipbuilding industry, HILS is employed for a range of usages, including power generation and distribution, dynamic positioning, thruster control, drilling operation control, and integrated automation systems. These services can markedly reduce the costs associated with incidents caused by partial and complete failures [22,25,26].

## 3. LNGC HILS Modeling

### *3.1. Specification of PMS Physical Modeling*

The PMS installed in an LNG vessel distributes, manages, and monitors power supplied from the generator to each load in the ship. It is crucial to effectively control and manage the ship's power system to ensure safety, security, and life support for individuals on board (critical loads), as well as maintain power quality for non-critical loads in accordance with international conventions, laws, and standards [29]. The main power equipment in an LNGC is categorized into the power supply section and the power consumption section. The power supply section contains two TGs and one DG, while the power consumption section contains the high-voltage (6600 V) section and the low-voltage (440 V) section. The 6600 V high-voltage section is composed of a side thruster, two compressors, eight cargo-hold pumps, and three ballast pumps, whereas the 440 V low-voltage section is composed of four general loads.

Detailed specifications of the devices are listed in Table 1. The specifications of the DG and TGs are based on the maximum output, voltage, and frequency of 3.45 MW, 6600 V, and 60 Hz, respectively. Additionally, simulation modeling was performed using MATLAB/Simulink (R2022a) based on the PMS modeling specifications listed in Tables 1 and 2.

**Table 1.** Detailed description of power supply [22].

| | Diesel Generator (DG) and Turbine Generator (TG) |
|---|---|
| Power | 3.45 MW |
| Voltage | 6600 V |
| Frequency | 60 Hz |

**Table 2.** Detailed description of power consumer [22].

| | Power (kW) | Voltage (V) | Frequency (Hz) |
|---|---|---|---|
| Bow Thruster (BT) | 1800 | 6600 | 60 |
| Cargo Pump (CP) | 530 | 6600 | 60 |
| Ballast Pump (BP) | 330 | 6600 | 60 |
| Lumped Load (LL) | 1000 | 440 | 60 |

## 3.2. Physical Modeling of Power Generation

The marine generator is modeled in the same physical model as the actual generator, and the output of the generator reaches 3.45 MW. As illustrated in Figure 4, the DG and TGs require the generator rated speed and the generator speed at output $P_m$ (mechanical power), whereas the field voltage calculator requires the generator rated speed and generator speed at output $V_f$ (field voltage), and three-phase voltage through a synchronous device.

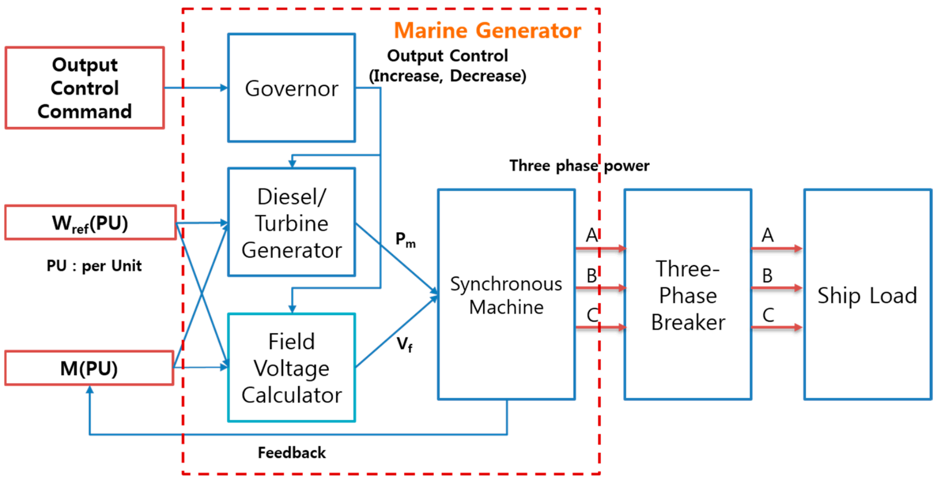


**Figure 4.** Modeling logic description of power supply.

The graph in Figure 5 shows the output of the designed DG, depicting the power, current, frequency, and voltage. An initial load of 1 MW was applied and stabilized quickly after starting generator operation, and then stabilized within 5 s even at a load of 0.5 MW. We confirmed that it takes some time for the DG to stabilize in terms of the operating characteristics.

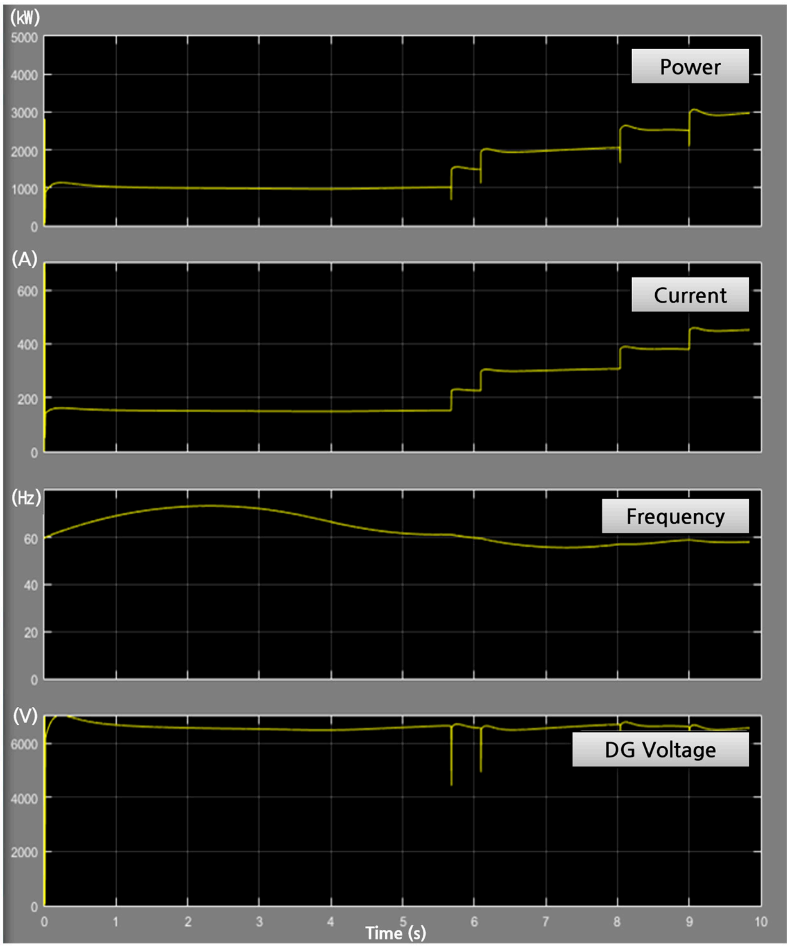


**Figure 5.** Simulation verification of the power supply model.

### 3.3. Physical Modeling of Power Consumsion

The bow thruster is a device for improving the ship adjustment performance when a ship stops or during low-speed navigation. The bow thruster is a typical power consumption equipment. Since it is possible to control the movement of the bow or stern when the ship is stationary, the ship is also easy to navigate in a port or shore without towing. Additionally, the bow thruster is a heavy load with a high power consumption from the perspective of the PMS.

As shown in Figure 6, the bow thruster simulation model is implemented as a physical model of the actual equipment used in the ship, and three-phase power is received as the input and transmitted to a cage induction motor via a three-phase circuit breaker. Here, the input value of the mechanical torque varies with the blade angle of the thruster, and the mechanical output value also varies.

The mechanical output ($T_m$) of the thruster varies with the mechanical torque of the thruster. The final output of the thruster depends on the stator current ($I_s$), rotor current ($I_r$), electric torque ($T_e$), and angular velocity ($\omega_m$).

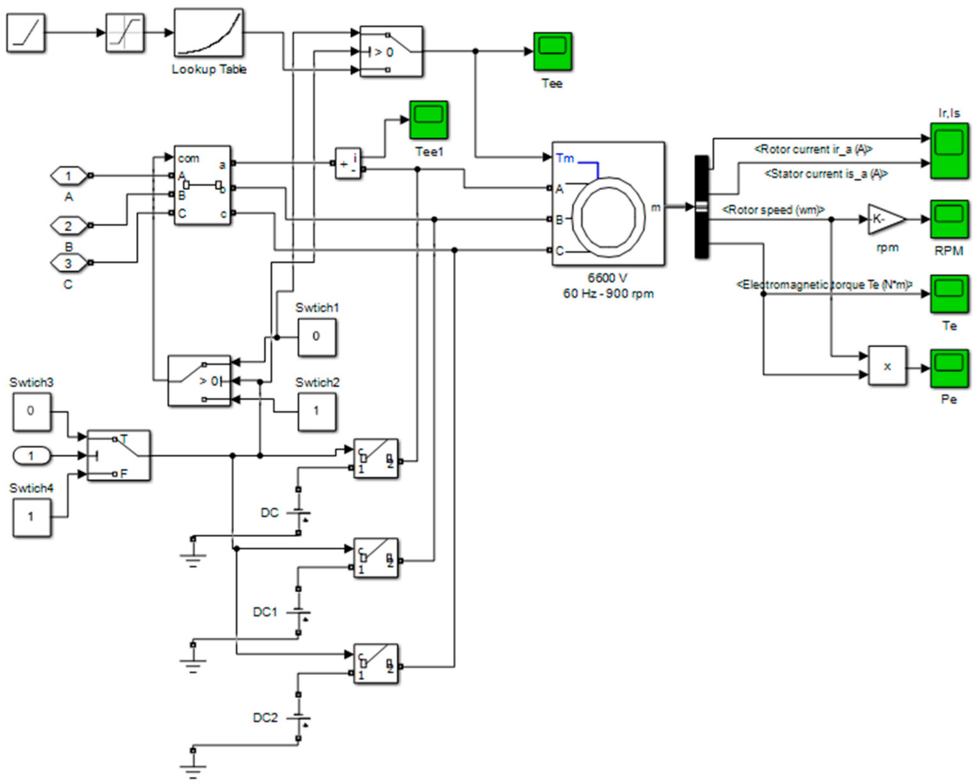


**Figure 6.** Modeling logic of the heavy consumer model.

For ease of control and analysis of the squirrel cage induction motor used in the thruster, the three-phase variable of the abc coordinate system is converted into the dq axis stationary coordinate system. When the dq axis voltage of the stationary coordinate system is converted into the dq axis voltage of the synchronous coordinate system, the coordinate axis is rotated in synchronism with the rotary system.

$$V_{ds}^{e} = R_s i_{ds}^{e} + \frac{d}{dt}\lambda_{ds}^{e} - \omega\lambda_{qs}^{e} V_{qs}^{e} = R_s i_{qs}^{e} + \frac{d}{dt}\lambda_{qs}^{e} - \omega\lambda_{ds}^{e} \quad (1)$$

The variables are represented as DC components, and the time-varying coefficients are removed. The dq synchronous coordinate system, which is converted to the stationary coordinate system and then to the synchronous coordinate system, is given in Equation (1).

In Equation (1), $i_{ds}^{e}$ denotes the d-axis current of the stator, $i_{qs}^{e}$ denotes the q-axis current of the stator, $\lambda_{ds}^{e}$ denotes the d-axis flux linkage of the stator, $\lambda_{qs}^{e}$ denotes the q-axis flux linkage of the stator, and $\omega$ symbolizes the angular velocity.

Additionally, the stator flux linkage $\lambda_{ds}^{e}$ is generated by the stator reactance $L_s$ and the mutual reactance $L_m$, as expressed in Equation (2):

$$\lambda_{ds}^{e} = L_s i_{ds}^{e} + L_m i_{dr}^{e} \lambda_{qs}^{e} = L_s i_{qs}^{e} + L_m i_{qr}^{e} \quad (2)$$

The terms $i_{dr}^{e}$ and $i_{qr}^{e}$ represent the d-axis and q-axis current of the rotor, respectively. The dq synchronous coordinate system, which is obtained by transforming Equation (2) to the stationary coordinate system and then to the synchronous coordinate system, is given in Equation (3):

$$V_{dr}^{e} = 0 = R_r i_{dr}^{e} + \frac{d}{dt}\lambda_{dr}^{e} - (\omega - \omega_r)\lambda_{qr}^{e} V_{qr}^{e} = 0 = R_r i_{qr}^{e} + \frac{d}{dt}\lambda_{qr}^{e} - (\omega - \omega_r)\lambda_{dr}^{e} \quad (3)$$

The term $R_r$ denotes the rotor winding resistance and $\omega_r$ refers to the rotor angular velocity. The dq axis variable in the synchronous coordinate system is given in Equation (4):

$$T_e = \frac{P}{2}\frac{3}{2}L_m\left(i_{qs}^e i_{dr}^e - i_{ds}^e i_{qr}^e\right) = \frac{P}{2}\frac{3}{2}\frac{L_m}{L_r}\left(\lambda_{dr} i_{qs} - \lambda_{qr} i_{ds}\right) \quad (4)$$

Figure 7 illustrates the waveforms of the output power, motor torque, rotor, and stator current of the thrust propeller. Increasing the blade angle from 0° to 23° increases the torque command exponentially and maximum torque is achieved at a blade angle of 23°. When the motor operation switch is opened after a predetermined time, the voltage and current input to the motor are cut off by the operation of the braking system, and the speed becomes zero. Normal operation of the motor is restored once the switch is closed again. We verified that the maximum motor output power of the bow thruster was 1.8 MW.

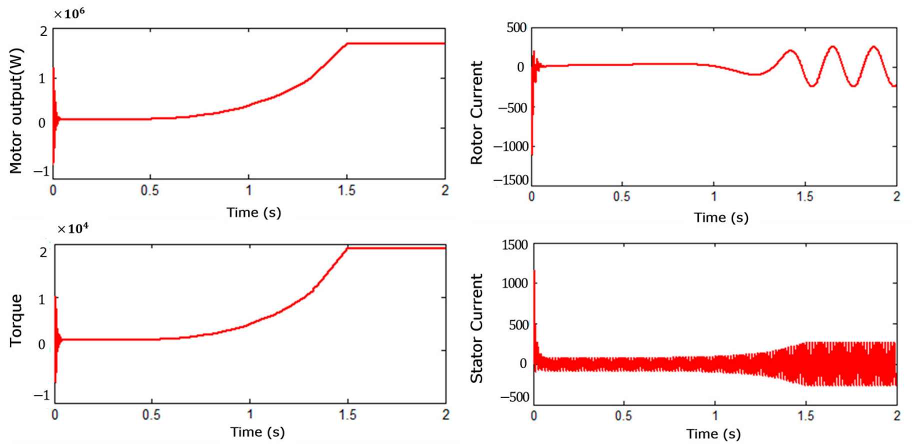


**Figure 7.** Simulation verification of heavy consumer model.

MATLAB/Simulink-based power system simulation models are depicted in their entirety in Figure 8. The models were developed using Simscape Electrical libraries(R2022a), which contain power model libraries for easy modeling. They were classified into three groups, namely, the power supply, port-side heavy consumer, and starboard-side heavy consumer.

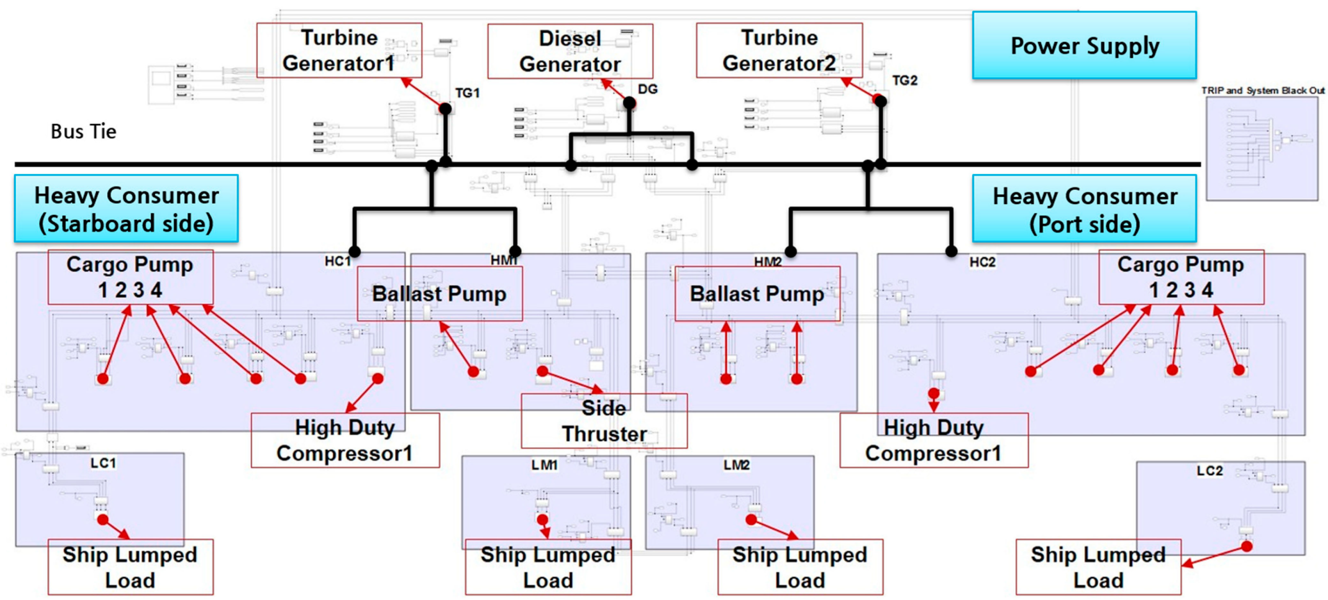


**Figure 8.** Integrated HIL simulation model of the power supply and heavy consumer.

## 4. Design and Development of PMS HILS Test Bed

### *4.1. Design of PMS-HIL Simulator*

The PMS controller used in this study was a PMS2500 from KTE Co., Ltd, Busan, South Korea [27]. The PMS-HIL simulation was implemented to create an environment similar to that of the LNGC. The MSBD, as shown on the left side of Figure 9, is located in the engine control room (ECR) and functions as an alarm monitoring system, as well as other control equipment to identify defects and malfunctions. As depicted on the right side of Figure 9, the SCC layout is divided into four distinct groups, namely, the power monitor, power supply, power consumer 1, and power consumer 2, to facilitate easy monitoring and simulation.

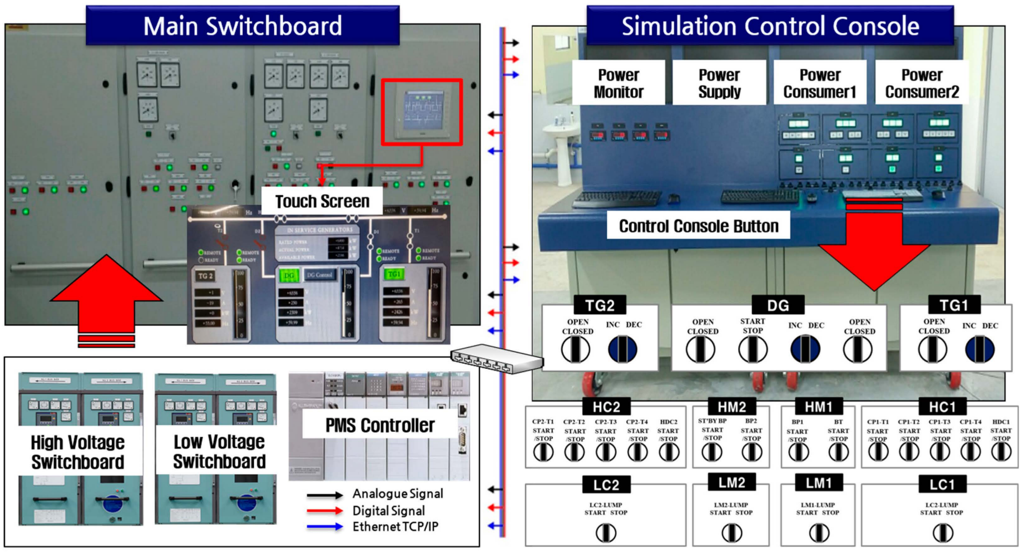


**Figure 9.** Integrated HIL test bed for the LNGC power management system.

The MSBDs are regarded as the central means for controlling the power, including the organized means for power source protection. The protection and switching of transformers, generators, and distribution feeder lines are typically conducted for the protection of high- and low-voltage power circuits [22]. The MSBD operates based on the operating current values in the power simulation, which interfaces with PXI and SCC, as shown in Table 3. Table 3 indicates that the analog values in the simulation are transformed into fixed values through electrical wiring. The PMS-HIL simulator utilizes National Instrument (NI) PXI hardware with the Phar Lap ETS, LabVIEW Real-Time Operating System (RTOS), and NI VeriStand. The error injection algorithm for the PMS-HIL was implemented using MATLAB/Simulink, and the user interface was developed and integrated as shown in Figure 9.

**Table 3.** Hardwire conversion table between the simulation model and main switchboard.

| | **Simulation Model** | **Main Switchboard** |
|---|---|---|
| Voltage | 0~8000 V | 4~20 mA |
| Frequency | 55~65 Hz | 4~20 mA |
| Power | 0~4500 kW | 4~20 mA |
| Current | 0~380 A | 4~20 mA |

Figure 9 is organized into two main sections. The left side of Figure 9 is the PMS controller and Main Switchboard (MSBD), which is the target of the HIL simulation, and the MSBD consists of a high-voltage MSBD and a low-voltage MSBD. The PMS controller and MSBD on the left perform the main functions of the MSBD on board the LNGC. The right section is the HIL simulator and simulation control console. The core HIL simulator performs power generation and power consumption functions to test the PMS controller. The implementation of power generation functions involves the use of on/off functions for two turbine generators and one diesel generator, as well as power increase and decrease functions. The power consumption function is divided into high-voltage and low-voltage components. The high-voltage component includes a bow thruster, eight cargo pumps, three ballast pumps, and two high-pressure compressors. The low-voltage component comprises four lumped loads situated on the port and starboard sides, and it is also equipped with load start and stop functions to fulfill the functions of each power consumption.

The simulator under consideration assesses the output voltages, frequencies, and currents in PXI, which enables the delivery of genuine analog signals in the LNGC. Analog signals are linked through hardwiring, while digital signals are transmitted to the PXI, Allen Bradley PLC, and the server workstation using the OPC client/server method, as depicted in Figure 9. The OPC server in LabVIEW guarantees a minimum scan time that adheres to a PMS communication time of 100 µs. The simulation model is implemented as a field-programmable gate array (FPGA) to fulfill the PMS communication time of 100 µs for the OPC server. This enables a realistic simulation execution time and simulation intelligence to be pursued, and real-time simulation performance can be guaranteed even in more complex simulations. Figure 9 shows the design of an external interface that can be linked with the MSBD and SCC. Data acquisition and simulation model control with external interfacing can be realized. The SCC includes the power supply and heavy consumer consoles required to control the PMS, which can detect malfunctions in the PMS through fault signal injection.

Figure 10 describes the configuration of the test bed network. The configuration is based on bidirectional communication with the target system and is configured to exchange digital and analog signals with the main switchboard. Power, voltage, current, and frequency are analog signals and the remainder are digital signals.

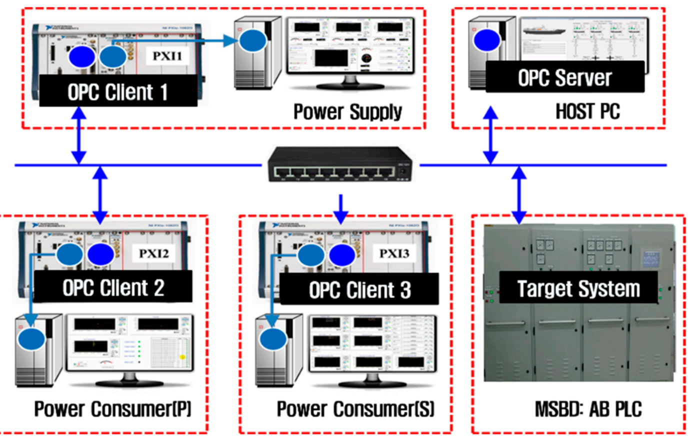


**Figure 10.** Network configuration of the PMS-HIL test bed.

The simulator possesses a human–machine interface (HMI) comprised of two monitoring user interfaces (UIs) developed using HTML. The first interface, designated for condition monitoring, displays pertinent data, including the air circuit breaker status, power supply, and consumer voltage, current, and power, as depicted in Figure 11. The HMI is linked to the parameters of the programmable power equipment in PXI. The values for circuit breaker conditions are conveyed as Boolean signals, while the values for power supplies and consumer outputs are represented by Double signals. Communication between the HMI and the power equipment is facilitated via the Modbus TCP. The second monitoring UI examines the circuit condition values based on test cases, enabling the user to evaluate a specific condition at a particular time or in the past. This differs from real-time monitoring, where the user is unable to ascertain the time elapsed. Furthermore, the analytical monitoring UI can promptly identify specific conditions and situations in the case of an unexpected occurrence.

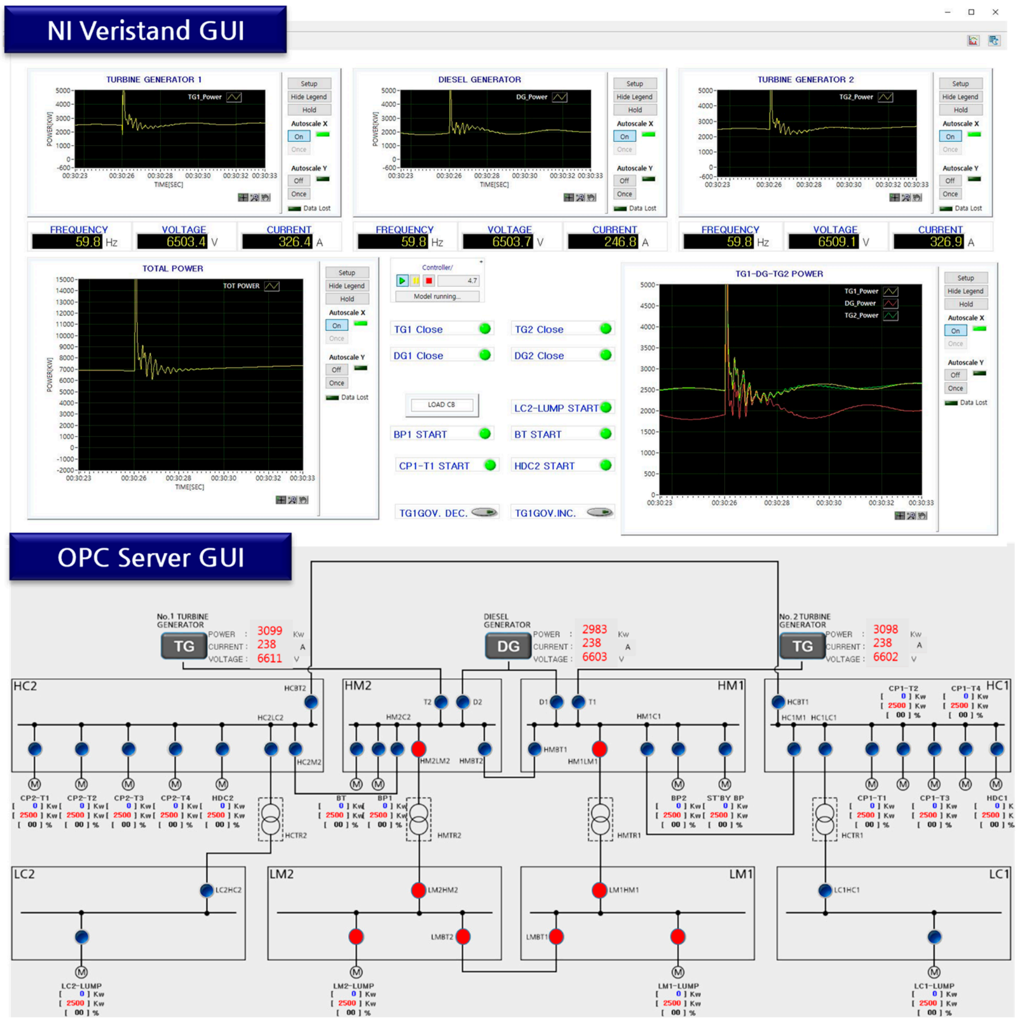


**Figure 11.** Condition monitoring GUI of the PMS-HIL test bed. Blue circles means 'connected or on' and red circles means 'disconnected or off'.

### 4.2. PMS-HIL Test Results

The LNGC PMS was evaluated using an actual test conducted in a PMS-HILS environment and verified in accordance with the functional design specifications presented by the classification society. Performance verification for basic circuit breaker control between the generator control and PMS was performed through load-sharing, governor, and parallel-operation tests.

Figure 12 presents the result of a test to determine whether the on/off buttons on the server side directly drive the lamps of the MSBD as a result of testing the feasibility of the circuit breaker remote control. We confirmed that the real-time operation is satisfactory. The power parameters of the 6600 V high-voltage load stage, including the DG and TGs, and the low-voltage section of 440 V can be verified and controlled through the circuit breaker.

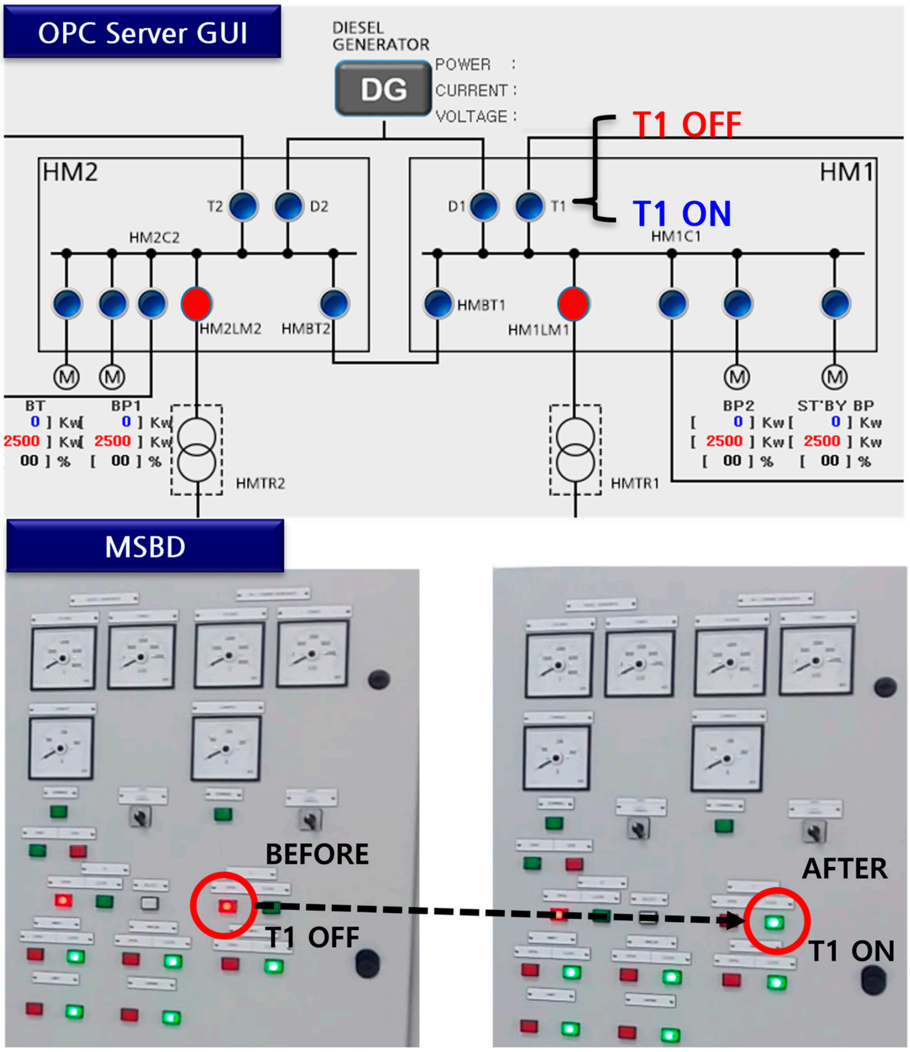


**Figure 12.** Air circuit breaker test of the main switchboard (MSBD).

4.2.1. Load-Sharing Test

Load sharing is fundamentally crucial in evaluating the overall PMS performance. The present work primarily focused on conducting a load-sharing test, which classified load sharing into the following three categories: symmetric, asymmetric, and fixed-load sharing.

The generator performance depends on the state of the power system, which is either symmetric or asymmetric. In symmetric mode, the power output ratio of each generator remains consistent during parallel operation. Conversely, in asymmetric mode, the power output ratio is uneven. The PMS makes the decision based on the status of the power system for maximum efficiency. Figure 13 depicts the load-sharing test outcomes in symmetric mode.

In the symmetric load-sharing test, TG1 was set as master, while TG2 and the DG operated in slave mode. The simulation was conducted for 20 s. Starting at an initial power of 7000 kW, a load of 1 MW was applied to the PMS through the simulator. It can be observed that it stabilized 18 s after load sharing was initiated at 5 s. The characteristic of a DG is such that it behaves more lightly than TG2.

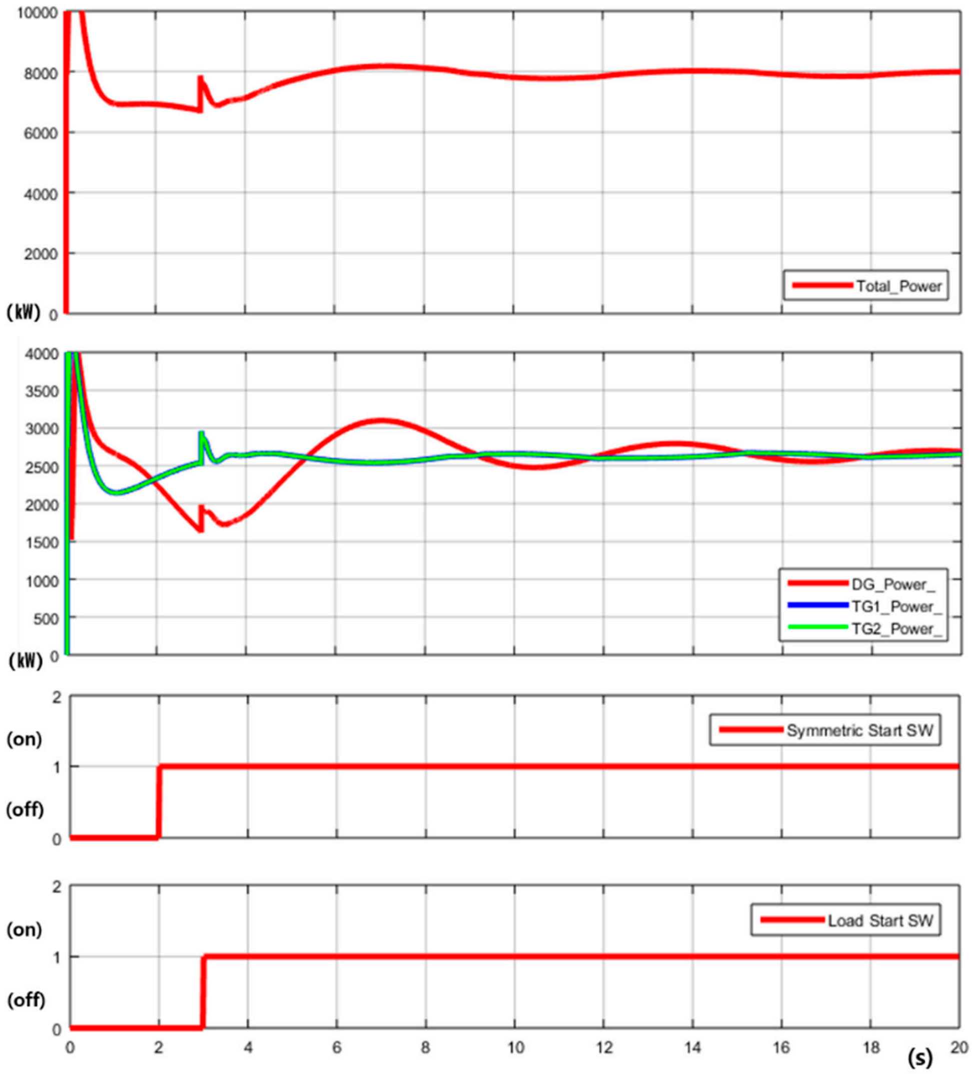


**Figure 13.** Symmetric load-sharing test.

In the asymmetric load-sharing test, as illustrated in Figure 14, TG1 was set as master, while TG2 and the DG operated as slave. The simulation was conducted for 20 s. Starting at an initial power of 6000 kW, a load of 1 MW was applied to the PMS through the simulator. The first cargo pump (530 W) and second cargo pump (530 kW) loads were applied in 8 s after waiting for stabilization at 75%. Load sharing in fixed mode can identify similar behavior to load sharing in asymmetric mode.

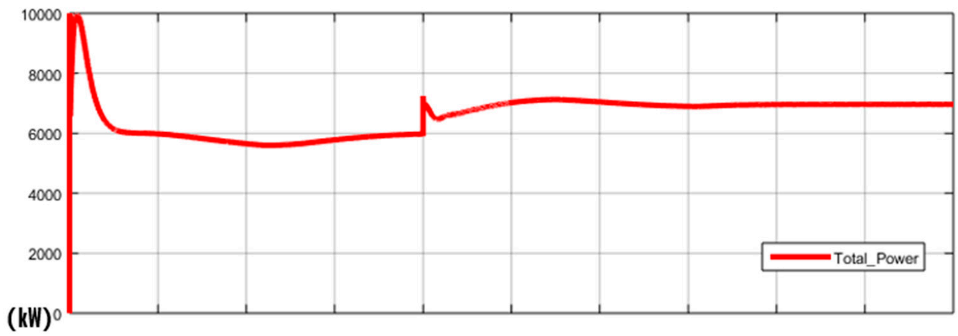


**Figure 14.** *Cont*.

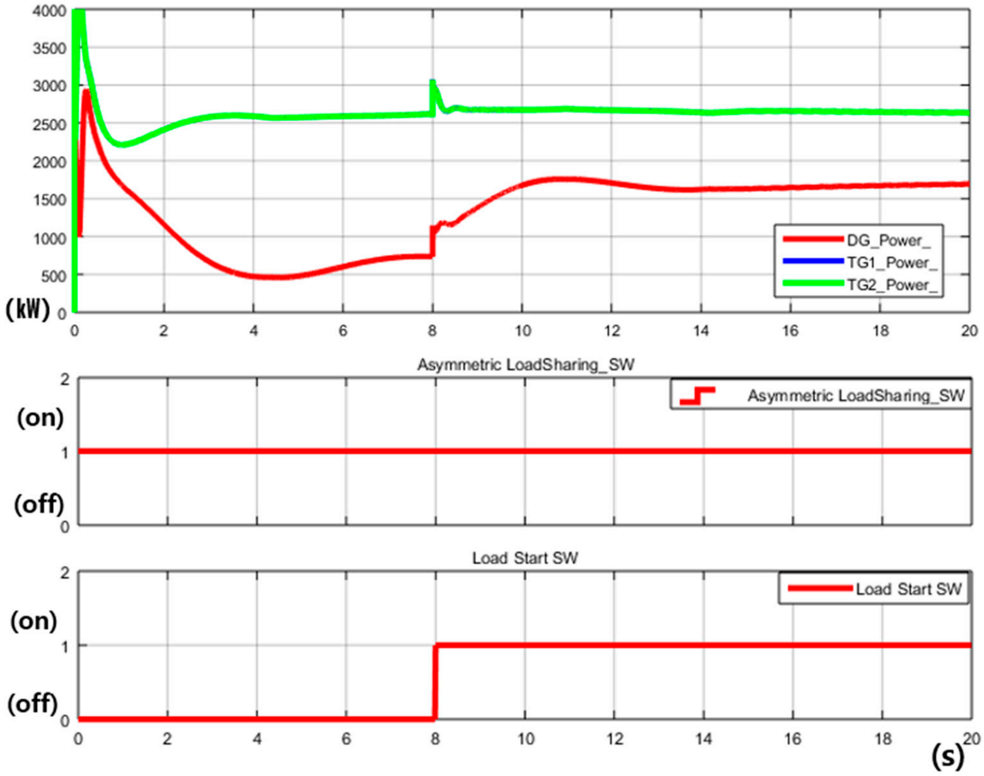


**Figure 14.** Asymmetric load-sharing test.

#### 4.2.2. Load-Dependent Start Test

To avoid a blackout, the generating capacity should surpass the load. Moreover, the PMS should initiate the backup generator once the load attains 80% of the rated power of the generator.

An initial load of 5.1 MW was applied by the PMS and two turbine generators were started. When the load exceeded 80% of the rated power of TG1 and TG2, the load start signal was triggered and the DG was started by the PMS at 4 s, and the two cargo pumps were loaded to 1060 kW at 5 s. The DG power increased at 4 s after the load was applied and stabilized after 3 s, as illustrated in Figure 15.

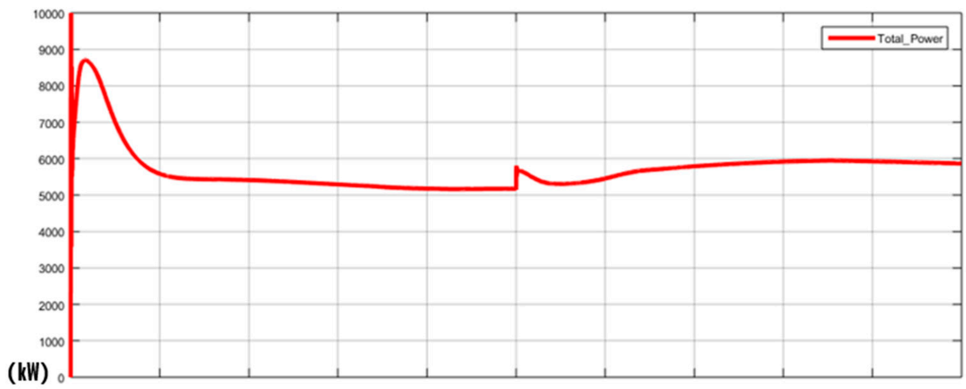


**Figure 15.** *Cont.*

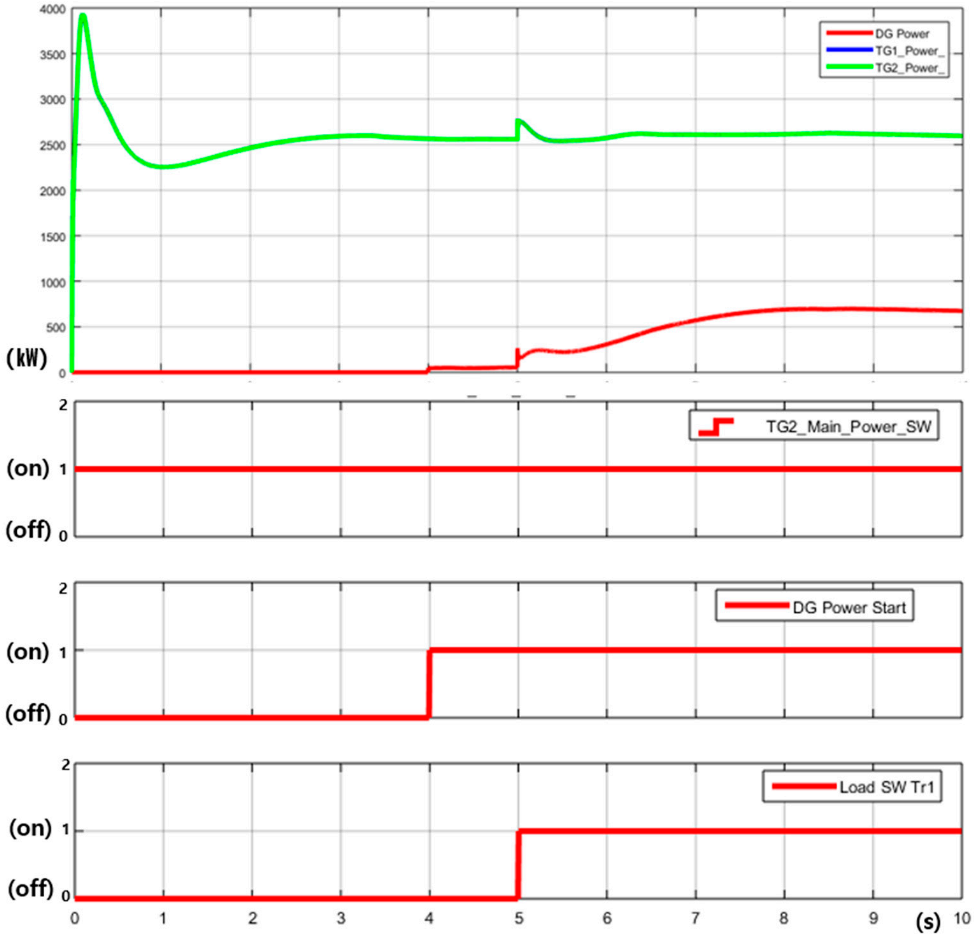


**Figure 15.** Load-dependent test.

4.2.3. Blackout Prevention Test

The primary function of the PMS is to prevent blackouts. If TG2 trips at 3 s due to the abnormal behavior of the load during the operation of TG1 and TG2, the PMS detects it and initiates power recovery by starting the DG at 4 s. Upon synchronizing, the DG is connected to the grid to increase the available power.

Although TG2 is shut down, TG1 and the DG maintain the total required power of 5 MW. Figure 16 shows the stabilization at approximately 10 s after the DG starts.

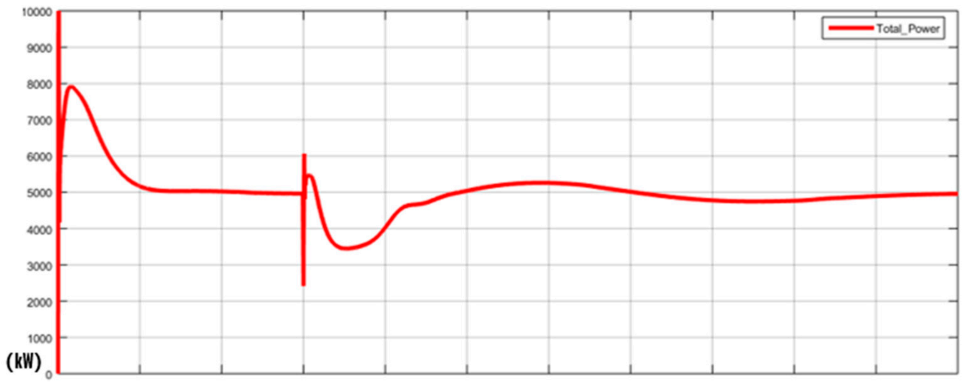


**Figure 16.** *Cont*.

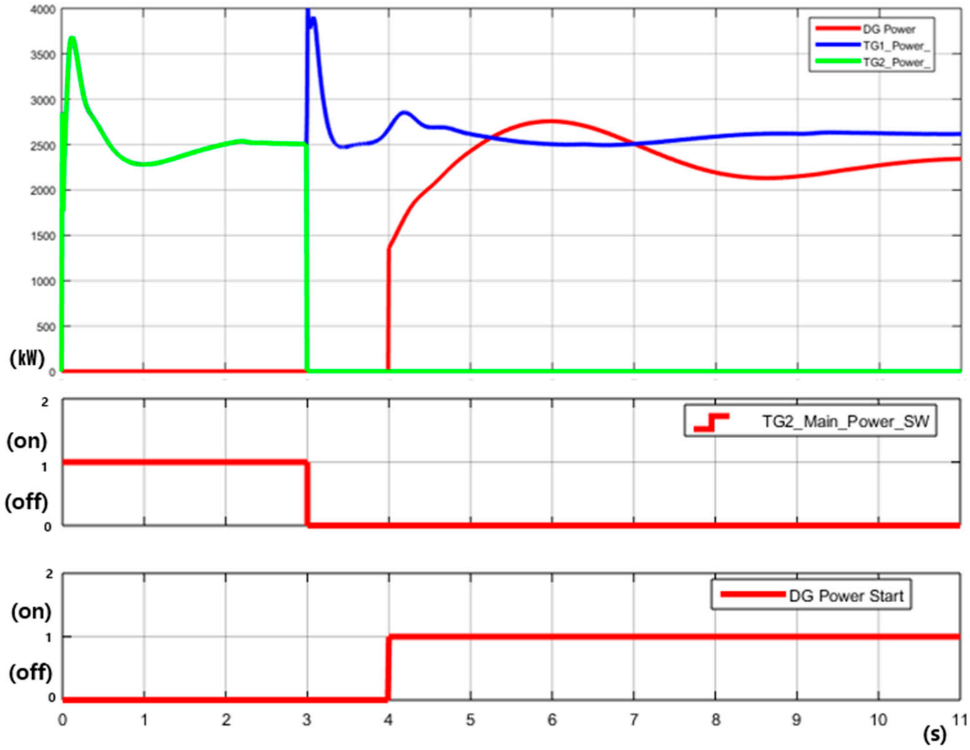


**Figure 16.** Blackout prevention test.

#### 4.2.4. Preferential Trip Test

The preferential trip test is a vital step in the PMS evaluation. When the PMS detects a power shortage with TG2 shutting down, it determines the priority of the trip based on the importance of the equipment. The priorities are classified into three groups, namely, PT1, PT2, and PT3, as listed in Table 4. The conditions are specified as follows:

(1) The load power exceeds 100% for each time delay (Table 4).
(2) The bus frequency is very low (frequency < 57.5 Hz for 5 s)
(3) Any circuit breaker trip of the generator when two or three generators are online.
(4) <Bow thruster pitch reduction> is activated when any generator fails in parallel running.

**Table 4.** Preferential trip condition.

| | Description | Capacity | Time Delay (s) |
|---|---|---|---|
| PT1 | No. 1, 2 Air Conditioner Compressor | 230 kW × 2 | 5 |
| | 440 V/220 V Galley Equipment | 150 kW | 5 |
| | Air Handling Unit | 52 kW × 2 | 5 |
| | Package Air Conditioner | 6.85 kW | 5 |
| | No. 1, 2 Package Air Conditioner For ECR | 9.0 kW | 5 |
| | Package Air Conditioner | 14.75 kW | 5 |
| | No. 1, 2 Ballast pump | 330 kW | 5 |
| | STBY Ballast pump | 330 kW | 5 |
| | Bow Thruster pitch reduction | 1800 kW | 5 |
| PT2 | STBD Cargo pump for No. 1, 2, 3, 4 C/TK | 530 kW | 10 |
| PT3 | PORT Cargo pump for No. 1, 2, 3, 4 C/TK | 530 kW | 15 |
| | No. 1, 2 H.H.P for AFT deck machinery | 129 kW | 15 |

The preferential trip function is activated after 5 s at an initial load of 6 MW. A ballast pump (BP), side thruster (ST), and cargo pump (CP) are tripped in the order of the above four conditions. The DG power fluctuation occurs more severely on the side of the thruster trip than on the ballast pump and the cargo pump because the side thruster is a heavy load of 1.8 MW. The total power stabilizes after 25 s, as shown in Figure 17.

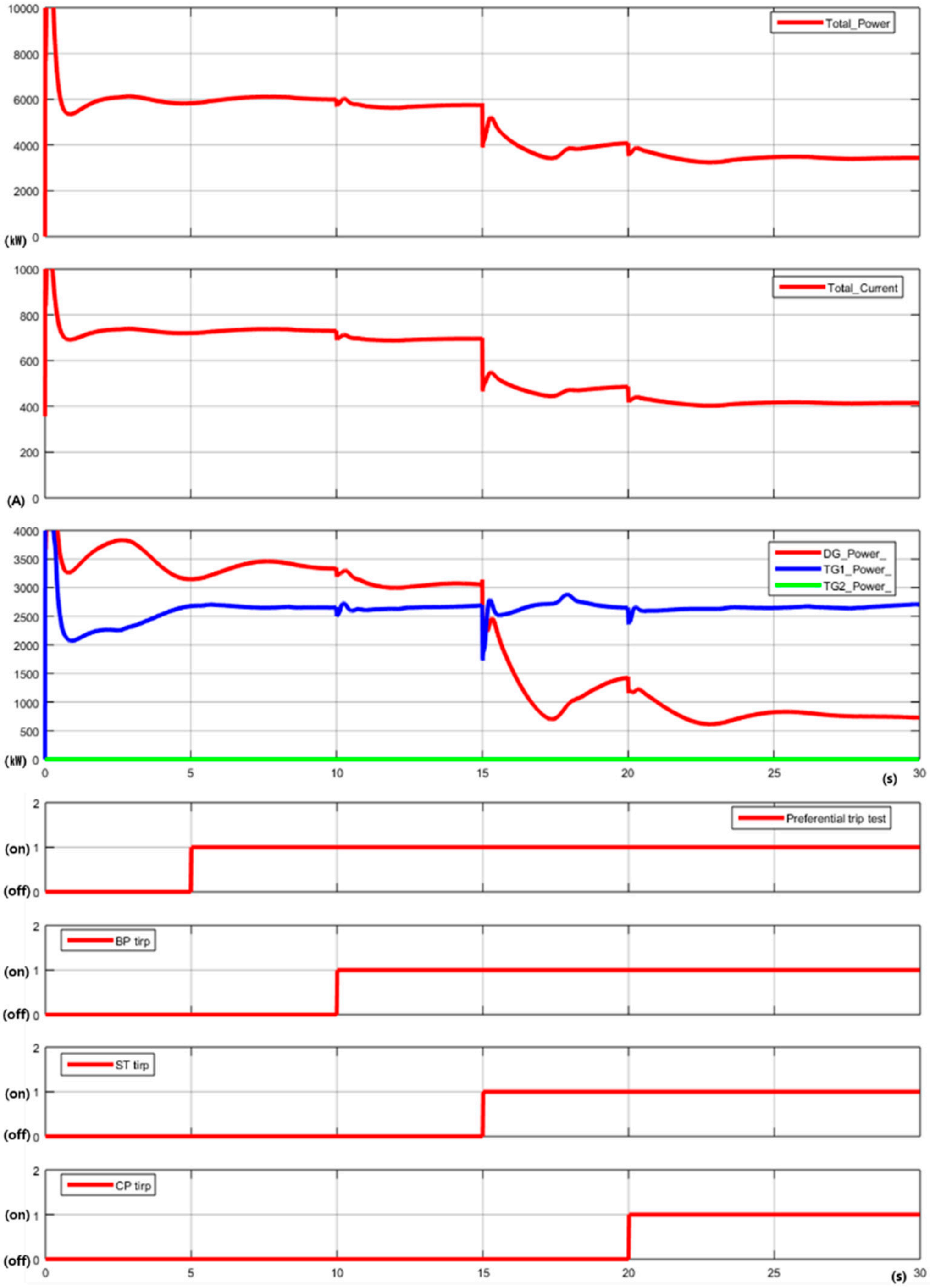


**Figure 17.** Preferential trip test.

## 5. Conclusions

LNGC orders are on the rise due to stricter marine environmental regulations. The complexity of the integrated system used in shipbuilding has increased significantly, resulting in a higher degree of automation and an increase in software errors. HILS, a well-known evaluation technique utilized in various fields, presents a crucial solution for evaluating the PMS of an LNGC. Compared to conventional acceptance tests, the HILS test bed is more cost-effective, faster, easier to reproduce, and safer.

This research presented a novel PMS-HILS test bed that is distinct from existing simulators.

(1) The proposed HILS platform employs genuine equipment data from the marine industry to create a realistic LNGC environment.
(2) The system establishes bidirectional communication between the SCC and MSBD using OPC server/client technology via Ethernet communication.
(3) The HILS system includes an Internet-based monitoring feature for convenient remote monitoring.
(4) The main elements of the LNG vessel were simulated using MathWorks software to perform HILS.
(5) The power generation model was composed of two turbo generators (TGs), a diesel generator (DG), and governor.
(6) The power consumption model included bow thrusters, cargo pumps, ballast water pumps, and lumped loads, which are primarily utilized in the LNGC.
(7) The system was validated and tested to perform load-sharing, load-dependent start, blackout, and preferential trip tests using the proposed HIL test bed.
(8) The evaluation of the proposed system demonstrated its significant potential for the commissioning of the PMS.

In the future, the system will be tested using diverse PMS test cases to expand its applicability to additional scenarios. During the testing phase, the modeling of induction motor starting transients will be refined to improve the accuracy, which is currently a limitation that requires further research. Moreover, the development of the system for ship automation will incorporate PMS control along with an energy management system.

**Funding:** This research was funded by the Kyungnam University Foundation Grant, 2020.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author due to privacy.

**Acknowledgments:** This research was supported by the Kyungnam University Foundation Grant, 2020.

**Conflicts of Interest:** The author declares no conflicts of interest.

## Abbreviations

| | |
|---|---|
| ABS | American Bureau of Shipping |
| AVR | automatic voltage regulator |
| SCC | simulation control console |
| C.TK | cargo tank |
| DNV | Det Norske Veritas |
| DP | dynamic positioning |
| ECR | engine control room |
| ECU | electronic control unit |
| FAT | factory acceptance test |
| EMS | energy management system |
| FDD | functional decomposition diagram |
| FPGA | field-programmable gate array |
| HHP | high holding power |
| HIL | hardware-in-the-loop |
| HMI | human–machine interface |
| HUT | hardware under test |
| HV | high-voltage |
| IMCA | International Marine Contractors Association |
| LNGC | liquefied natural gas carrier |
| LV | low-voltage |

| | |
|---|---|
| MCU | main control unit |
| MSBD | main switchboard |
| OPC | open platform communications |
| PCI | peripheral component interconnect |
| PLC | programmable logic controller |
| PMS | power management system |
| PQMP | program quantitative management plan |
| PXI | PCI eXtensions for Instrumentation |
| RAMS | Reliability, Availability, Maintainability, and Safety |
| RTDS | real-time digital simulator |
| SAT | software acceptance test |
| SCC | simulation control console |
| STBY | STandBy |
| SI | system integrator |
| SIL | software-in-the-loop |
| TD | technical description |
| VV | verification and validation |

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