

Test Platform Development of Vessel's Power Management System Using Hardware-in-the-Loop Simulation Technique

Sang-Jung Lee*, Sang-Kyu Kwak*, Sang-Hyun Kim**,
Hyung-Jun Jeon** and Jee-Hoon Jung†

Abstract – A PMS (Power Management System) controls vessel's power systems to improve the system efficiency and to protect a blackout condition. The PMS should be developed with considering the type and the capacity of the vessel's power system. It is necessary to test the PMS functions developed for vessel's safe operations under various sailing situations. Therefore, the function tests in cooperation with practical power systems are required in the PMS development. In this paper, a hardware-in-the-loop (HIL) simulator is developed for the purposes of the PMS function tests. The HIL simulator can be more cost-effective, more time-saved, easier to reproduce, and safer beyond the normal operating range than conventional off-line simulators, especially at early stages in development processes or during fault tests. Vessel's power system model is developed by using a MATLAB/SIMULINK software and by communicating between an OPAL-RT's OP5600 simulator. The PMS uses a Modbus communication protocol implemented using LabVIEW software. Representative tests of the PMS functions are performed to verify the validity of the proposed HIL-based test platform.

Keywords: Power system modeling, Power management system, Real-time simulation, HIL

1. Introduction

Recently, smart ship technology has been introduced using bigdata, Internet of Things (IoT), renewable energy, and Energy Storage System (ESS) [1-2]. With the technology development, the vessel's power system controllers such as Power Management System (PMS) and Energy Management System (EMS) have been more complicated [3]. In prototyping those controllers, the function tests of the controllers should be carried out under various conditions not only a normal condition but also fault situations. Therefore, an effective test platform which is necessary for the controller's function tests has attracted more attentions [4].

In many researches, various controllers were validated by model based design [5-6]. The model based design is a good test platform to verify controller before developing prototype. However, the model is not exactly the same as realistic hardware. Therefore, the simulation model cannot emulate the dynamic characteristics of the prototype completely.

Hardware-In-the-Loop Simulation (HILS) is advanced test platform to test actual hardware. In HILS platform, a system such as microgrid and electric machine is modeled

in Real-Time Digital Simulator (RTDS) in Fig. 1. The simulator can emulate the system by computing the model in real time. The simulator is interfaced with Hardware Under Test (HUT) such as a PMS and a power inverter. The HUT operates with virtual system in the simulator. This means a prototype, which is real hardware, can be tested with virtual system without real power system. The prototype can be operated in various condition by modifying the system model. Therefore, HILS supplies easily repeatable, cost-effective, and time-saving hardware function test environment [7]. Because of this advantage, HILS test platform is used in many field such as automobile, power electronics and microgrid [8-9].

In order to develop HILS platform, two technologies are important for accuracy and stability of HILS platform: modeling of system components and interfacing RTDS with HUT. In [3] and [9], modeling process of various system is described such as generator, battery and induction machine. The interface between RTDS and HUT depends on which hardware is tested. In Power HILS (PHILS) to test power hardware, the power interface between RTDS and HUT is critical in Fig. 1(a). The interface algorithm between power system model and electronic load is described [10-11]. In Controller HILS (CHILS) which tests controller, communication interface is important in Fig. 1(b). In [9] and [12], communication interface is studied for wind turbine and electric vehicle system.

In this paper, CHIL test platform for PMS is validated and the PMS function test is carried out in various condition. The complex power system is modeled to be

† Corresponding Author: School of Electrical and Computer Engineering, Ulsan National Institute of Science and Technology (UNIST), Korea. (jhjung@unist.ac.kr)

* Dept. of Electrical Engineering, Ulsan National Institute of Science and Technology (UNIST), Korea. ({lsj8154, tkdrb0414}@unist.ac.kr)

** Outfitting System Research Department, Hyundai Heavy Industries, Korea. ({sanghyun_kim, hyungjun.jeon}@hhi.co.kr)

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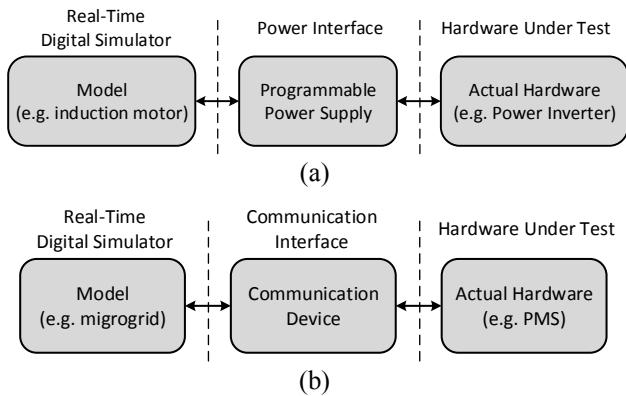


Fig. 1. Examples of HILS platform (a) Power HILS; (b) Control HILS

operated by PMS command. A communication interface between the PMS and virtual power system in the simulator is described. Finally, main PMS function such as load sharing, blackout prevention and load dependent start is demonstrated with the PMS HILS test platform.

2. Vessel's Power System

Fig. 2 shows single line diagram of vessel's power system. The power system consists of diesel generators, switchboards, transformer and generator controller such as governor and Automatic Voltage Regulator (AVR). In the power system, electric power is supplied from the generator and operation mode of generator varies depending on the load condition. In low load conditions, the generators operate alternately and when the load increases to a certain power level, the generator in standby mode simultaneously supplies power to the load to maintain maximum efficiency conditions of the generator. In order for the generators to operate in parallel operation, the generators must be synchronized. If the generators are not synchronized and supplies electric power simultaneously, the efficiency of the generator is greatly reduced due to the occurrence of active power unbalance and reactive power. So, synchronization is necessary process in vessel power system. Synchronization is the process of matching the frequency and voltage level to the running power network. It is processed by the switchboard, the AVR and the governor. AVR controls voltage level by adjusting excitation filed current and governor controls frequency and phase by adjusting diesel engine speed. When the voltage level, frequency and phase of the generator which is in standby mode become synchronized with target generator, synchronized generator is connected running network by the switchboard.

Blackout situation on a vessel is very serious issue. Because main functions in vessel such as propulsion, dynamic position can be stopped due to failure of power generation. When power required from load is larger than the power that the generator can produce, blackout

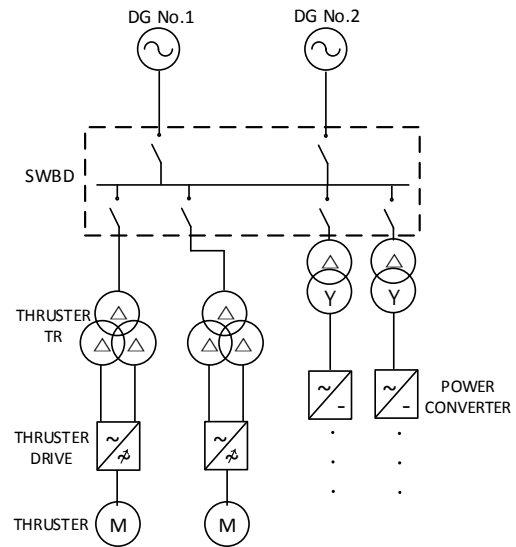


Fig. 2. Single line diagram of vessel power system

condition occurs. Therefore, the PMS is necessary to handle the power consumption and generation. The PMS supervises the load being demanded from whole system and establishes the power limits to protect blackout condition. In addition, it performs various functions to increase efficiency of power system.

3. Power System Modeling

The vessel's power system is modeled in MATLAB/SIMULINK. In modeling process, the characteristics of each component should be analyzed at first. Then, the components should be expressed as equivalent with mathematical equations. With the equations, the components can be modeled and parameter value from datasheet should be included in the model.

3.1 Main components of vessel's power system

3.1.1 Generator set modeling

The generator operates with diesel engine governor and Automatic Voltage Regulator (AVR) in Fig. 3. The derivation of equations and modeling process is described in [13-15]. The governor output is mechanical power to rotate generator rotor. The power is generated by a diesel engine in the governor. There are two inputs of the governor: W_{ref} (pu) is speed set point to make the rotor rotate in rated speed and W (pu) is the rotor speed. According to the difference of the input values, the governor adjusts fuel quantity of diesel engine to maintain rotor speed at rated.

AVR controls field voltage in the rotor. AVR has two inputs: V_{ref} and V_t . V_{ref} is voltage set point to make generator terminal voltage (V_t) rated voltage. The AVR output is generator field voltage calculated by the

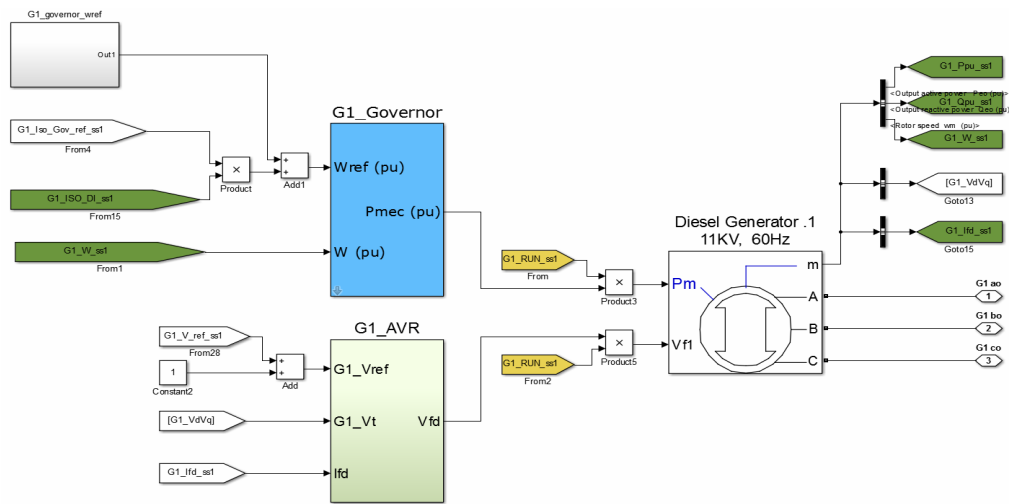


Fig. 3. Generator set model

difference of the inputs. The governor controls frequency of generator voltage and the AVR controls amplitude of generator voltage. The generator generates three-phase power by the mechanical power and field voltage input. The generator equations are as follows:

$$v_{qs}^r = -r_s i_{qs}^r + \omega_r \lambda_{ds}^r + p \lambda_{qs}^r \quad (1)$$

$$v_{ds}^r = -r_s i_{ds}^r - \omega_r \lambda_{qs}^r + p \lambda_{ds}^r \quad (2)$$

where ω_r is rotor angular velocity, λ_{ds}^r and λ_{qs}^r are magnetic linkage in the dq -axis, respectively. The voltage equations of (1) and (2) are expressed in the dq -axis.

3.1.2 Thruster drive

There are many kinds of loads in the vessel's power system. Thruster drive is representative load. Thruster drive is motor drive system and controls the vessel's position moved by wave. The detailed model is derived and described [16]. The thruster controller block includes controllers to estimate torque and the thruster drive block consists of motor drive system in Fig. 4. The motor is induction motor and the drive system has Direct Torque Control (DTC) controller. According to torque and speed set point inputs, the DTC controller calculates switching signal of the power inverter. The inverter supplies AC power to the induction motor from DC power and gate switching signal. From the AC power, induction motor makes mechanical power and fixes the vessel's position.

3.2 Control module modeling

3.2.1 Synchronization module

The generator voltages should be synchronized in parallel operation. However, the PMS just gives open/close signal of generator circuit breaker and does not control voltage for the synchronization. Therefore, synchronization

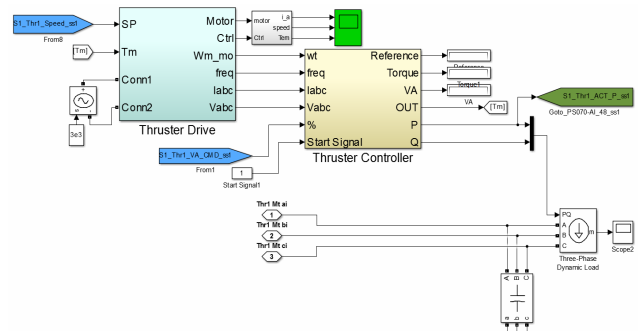


Fig. 4. Thruster drive model

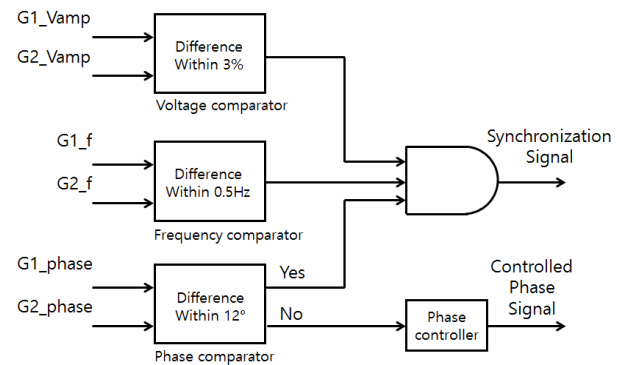


Fig. 5. Synchronization block diagram

module should be modeled. The synchronization means that amplitude, frequency and phase of the generator voltage are the same each other. The angle difference between the two voltages must be within 12 degrees, the amplitude difference should be within 3%, and the frequency difference must be within 0.5 Hz [17]. The Synchronization process is in Fig. 5. Before parallel operation, the PMS gives circuit breaker close command to connect generators. If synchronization module receives the command signal, it controls the generator voltage. When the voltages are synchronized, the circuit breaker is closed.

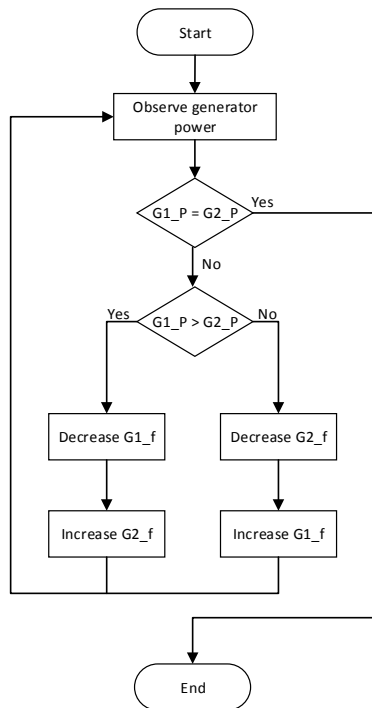


Fig. 6. Load sharing algorithm

3.2.2 Load sharing module

In parallel operation, generator should share supply power. In droop mode, the PMS controls generator frequency according to amount of load. However, the PMS does not control generator frequency in isochronous mode in which the frequency is not controlled according to load. Therefore, the load sharing module should be modeled for isochronous mode. The load sharing algorithm is in Fig. 6. Load sharing module monitors generator power. If the power of the generators is not the same, load sharing module controls the governor input which determines generator active power. After load is balanced, the load sharing module does not control the governor.

4. Parallel Computation

4.1 Concept

Since the vessel's power system model is complicated, a high performance RT simulator is required. There are multiple cores for the fast computation in the OPAL-RT's OP5600 simulator. The model should be divided into the individual cores and the cores perform the parallel computation. Fig. 7 (a) shows the model separation for the parallel computation. In the parallel computation, the computation time of the target model should be balanced. If not, an overrun error can be happened when the computation time is longer than the simulation time step.

Fig. 7(b) shows an ineffective model separation case. The total computation time is 70us but the first core

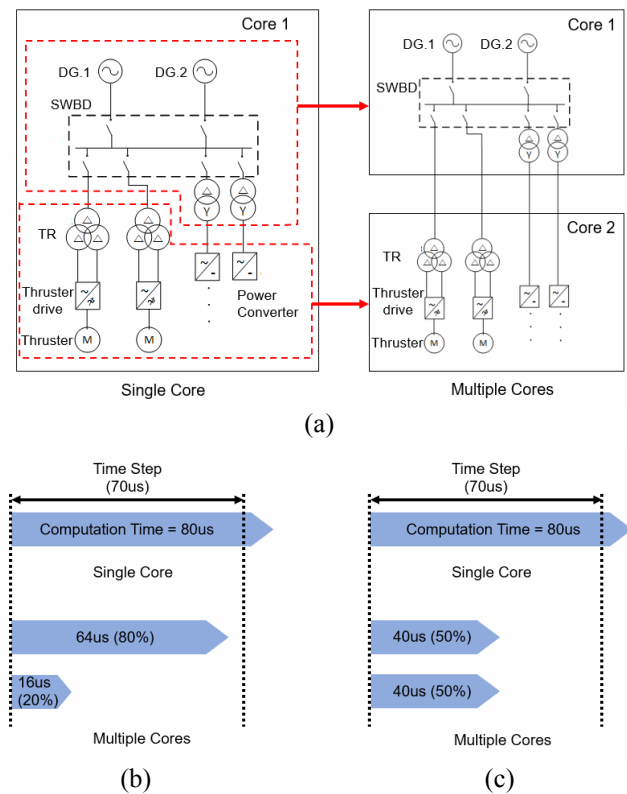


Fig. 7. Parallel model configurations: (a) Model separation, (b) Ineffective model separation; (c) Appropriate model separation

takes 80% of the entire model computation. It results in the overrun error, which means the computation time is longer than the simulation time step. Fig. 7(c) shows an appropriate model separation case. The computation time of each core should ideally be the same. However, it is difficult to obtain the perfect balance of the parallel models. Therefore, during the real-time model development, the model separation should be considered for the appropriate parallel computation.

4.2 Algebraic loop

The other important work is to minimize the number of algebraic loops among the parallel cores, which is shown in Fig. 8(a). The output signal of the first core goes into the input signal of the model in the second core. And then, the output signal is fed back to the first core. In the parallel computation, the signal which flows from one core to another core is delayed as much as a simulation time step. The time delay can increase dynamic errors, which can be propagated to execution errors in the simulation. The algebraic loop is also occurred in the separation of the power system model. This is because the separated power system models are inter-connected. Therefore, the appropriate model separation is significant to reduce the number of the algebraic loop. The model in Fig. 8(b) has one algebraic loop, however, the model in Fig. 8(c) has six

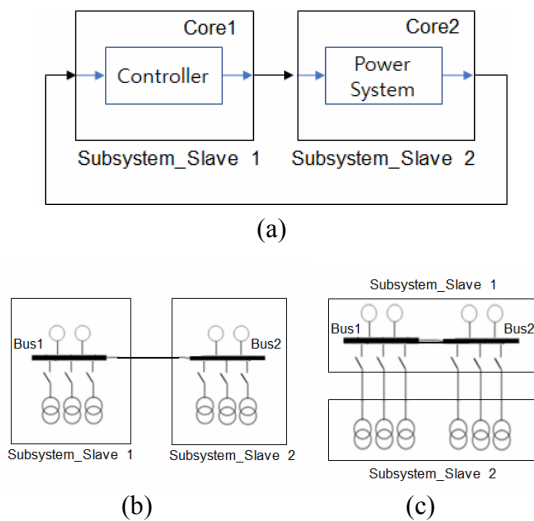


Fig. 8. Model separations: (a) Algebraic loop; (b) Simple algebraic loop; (c) Complicate algebraic loop

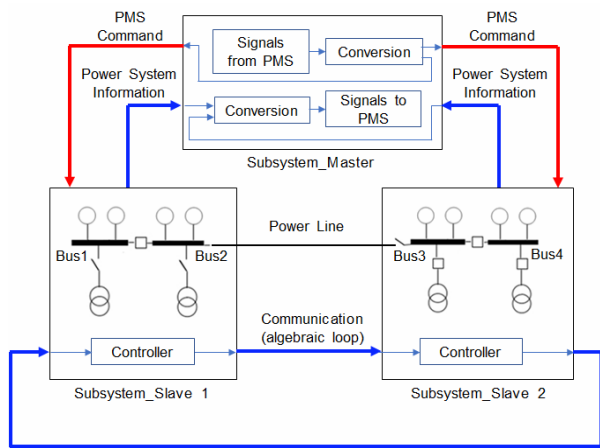


Fig. 9. Vessel's power system model using parallel computation

algebraic loops.

4.3 Model configuration of vessel's power system

In the proposed model of the vessel's power system, three cores are used for the parallel computation: the first core is a normal performance core and the others are high performance cores. Fig. 9 shows the configuration of the vessel's power system model. The normal core computes the subsystem master block. This subsystem is responsible for the signal processing between the power system model and the PMS. The signal type is converted to a Modbus protocol. The other cores compute the subsystem_slave 1 and 2 blocks. The power system model is complicated, so the model is computed by the high performance cores.

The model is divided into two parts and the cores take each half of the power system. The power system consists of four buses and each part has the same structure. In order to make a balance the computation time of each subsystem,

Device	IP Address	TCP Port
PMS1_PS070	172.20.101.31	502
PMS2_PS071	172.20.101.32	502
PMS3_PS072	172.20.101.33	502

IO List	StartAddress	Function Code	Number of Registers/Coils
PMS1_AO_70	0	16	24
PMS1_AI_70_1	48	3	60
PMS1_AI_70_2	108	3	60
PMS1_DO_70	298	16	8
PMS1_DI_70	314	3	18
PMS2_AO_71_1	0	16	11
PMS2_AO_71_2	11	16	8
PMS2_AI_71_1	19	3	37
PMS2_AI_71_2	56	3	44
PMS2_DO_71	100	16	14
PMS2_DI_71	114	3	39
PMS3_AO_72	0	16	24
PMS3_DO_72	24	16	8
PMS3_AI_72_1	32	3	60
PMS3_AI_72_2	92	3	11
PMS3_AI_72_3	103	3	60
PMS3_DI_72	163	3	17

Fig. 10. IP address and IO list of PMS

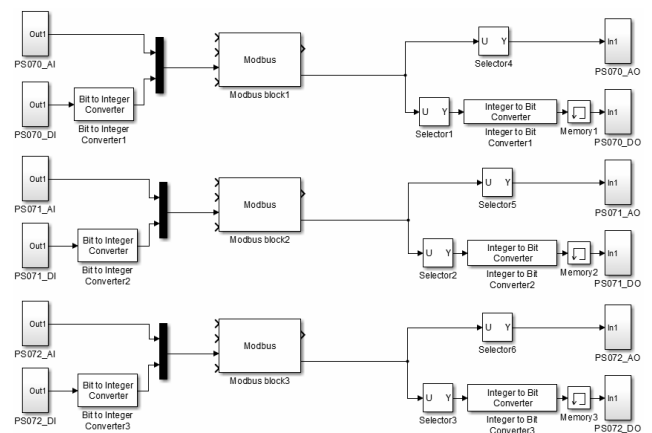


Fig. 11. Register map in Simulink

the cores are responsible for two buses. The model computation time of each cores was measured that the first core was 44.92 us, the second core was 59.46 us, and the third core was 58.70us, respectively. The time step was 70 us and the computation time of the high performance cores was well balanced.

5. HILS Implementation and PMS Test

5.1 Communication and interfacing

Three PMSs control the vessel's power system. Each PMS monitors and controls the part of the entire power system individually. In order for each PMS to independently control the power system, the electrical data should be distinguished and transmitted to each PMS. The

data processed by the PMS can be divided into analog and digital signals. Electrical data such as the grid voltage, current and power are classified into the analog and digital signals which are the ON/OFF signal of the switchboard and the governor's speed up and down signals.

Fig. 10 shows a register mapping for the analog and digital signals of the PMS. The register is mapped under the Modbus protocol through the TCP/IP.

In order for each of the PMS and the RT simulator to independently exchange the data, the communication block which has the same number of the PMS is required. Fig. 11 shows that the register mapping is performed on the simulation model by using Modbus communication block provided by RT-Lab software. Each Modbus communication block independently exchanges data with the PMS.

The Modbus protocol exchanges data in a Master-Slave relationship. The Modbus communication is not possible if the communication structure is configured as Master-Master or Slave-Slave. Fig. 12 shows communication structure in HIL system. Since the RT simulator and the PMS can only perform the role of Modbus Slave, the communication becomes impossible when two devices are directly connected to the same network. To solve the communication problem, two Masters and an intermediate data storage which can be shared by two Masters are added between the PMS and the RT simulator.

Fig. 13 shows the proposed communication structure for the HILS system. The boxed part is implemented by using LabVIEW software. The communication is performed as follows: Master 1 exchanges analog and digital signals with the RT simulator every 100 ms, and the signals are

stored in the intermediate storage. Master 2 acquires the signal requested by the PMS from the intermediate storage and transfers it to the PMS. The control signal transferred to the RT simulator by the PMS is updated by the intermediate storage. Then, the control signal is transmitted to the RT simulator by the Master 1.

5.2 PMS testing on HIL simulator

The main function of PMS is automation. The PMS monitors the power system and controls for safe operation. The purpose of the PMS test is to test the PMS function in various power system conditions. In the paper, three representative tests are described.

5.2.1 Load sharing test

Depending on the power system condition, the generator operates in symmetric mode and asymmetric mode. In symmetric mode, supply power ratio of each generator is the same in parallel operation. The asymmetric mode is the opposite case. The PMS selects the mode according to the power system condition for high efficiency operation. Fig. 14 shows load sharing test in the symmetric mode. The initial condition is that the power supplied by generator 1 is higher than the power supplied by generator 2. The PMS sends command signals to the governor to operate in symmetric mode. If the generator power is higher than the

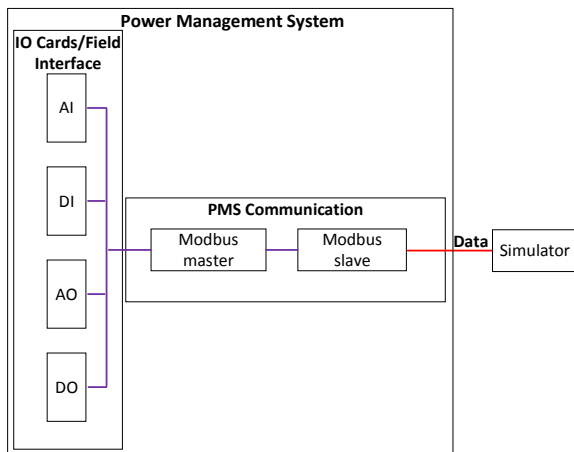


Fig. 12. PMS communication structure

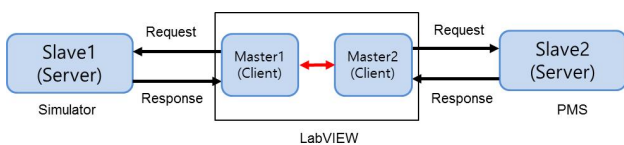
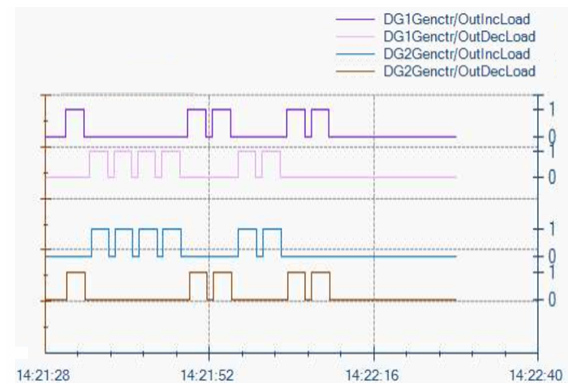


Fig. 13. Communication structure for HILS system



(a)



(b)

Fig. 14. Load sharing test: (a) Governor control signal; (b) Generator power

average power, the PMS will reduce the output of the governor and in the opposite case increase the output of the governor. Fig. 14(a) shows the signal for controlling the output of the governor. Fig. 14(b) shows the output power of the generator which changes in according to the control signal of the governor. If the amount of power supplied by each generator is the same, the PMS stops controlling the governor.

5.2.2 Load dependent start test

To avoid blackout conditions in the power system, the available power of the generator must be higher than the load. Therefore, to prevent blackout condition, the PMS must start the standby generator when the load reaches 80% of the generator rated power. This function is called load dependent start and Fig. 15 shows the test result. The initial condition is that generator 1 only supplies an increasing load. The load exceeds 80% of the generator rating at 3 [s] and the PMS starts the load dependent start function. The standby generator 2 is started by the PMS command signal. After synchronization, the generator 2 is connected to the grid at 5 [s].

5.2.3 Blackout prevention test

One of the most important function of PMS is blackout prevention. When the available power of generator is lower than load, blackout condition occurs. The blackout prevention function test is shown in Fig. 16. Under the initial condition, generator 1 and 3 supply power to the grid. After 2.1 [s], generator 1 is removed from the grid due to a

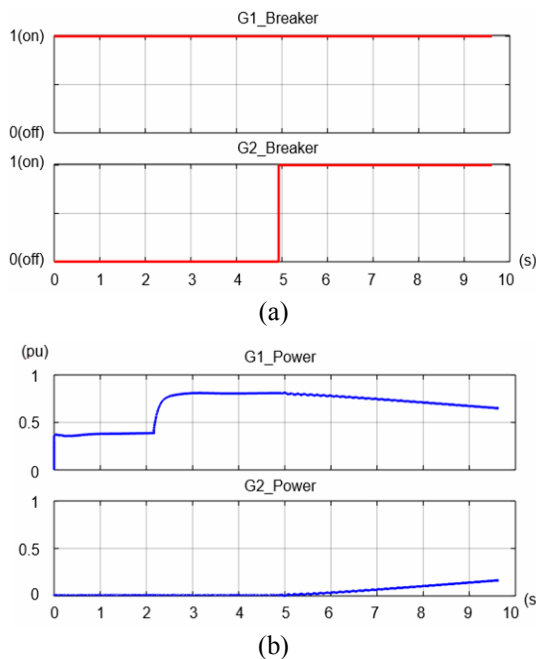


Fig. 15. Load dependent start test: (a) Generator circuit breaker status; (b) Generator power

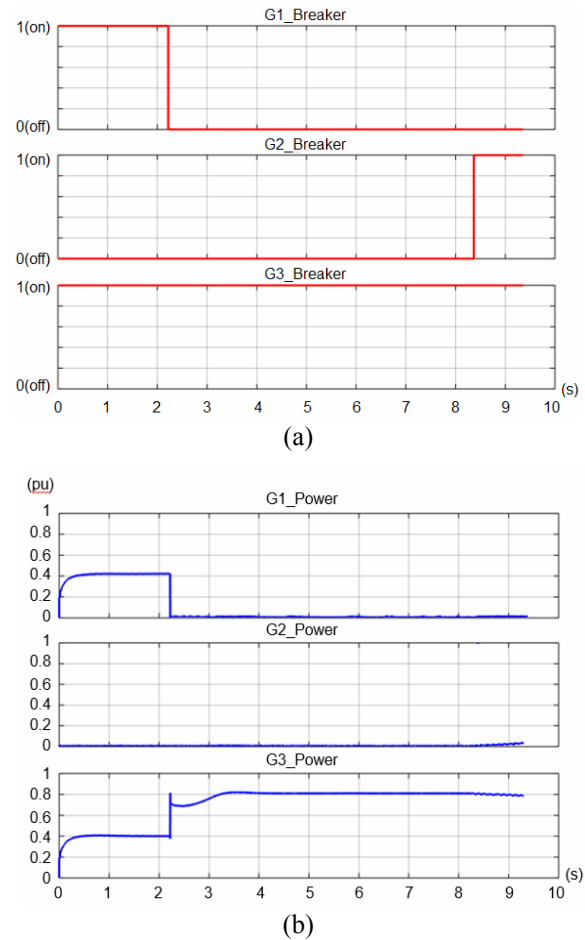


Fig. 16. Blackout prevention test: (a) Circuit breaker status; (b) generator power

system fault. After 2.1 [s], only the generator 3 is supplying power. Since the power supplied from the generator 3 is more than 80% of the generator rated power, the PMS detects the failure condition and starts standby generator. At 8.2 [s], generator 2 is connected to the grid after the synchronization operation is complete to increase the available power.

6. Conclusion

In this paper, the HIL test platform of vessel's PMS is developed. The virtual vessel's power system is modeled and simulated in the real-time digital simulator. For preventing the overrun error, the parallel computation method is adapted and the effective model separation method is applied to the vessel's power system model. LabVIEW program is used to interface the simulator and the PMS with Modbus protocol. The main function tests are performed to verify the validity of the proposed HIL-based test platform. As a result, cost-effective, time-saving PMS test can be carried out. Also, this HILS test platform can help fast prototyping of vessel's PMS.

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Sangjung Lee received the B.S. degree in electrical engineering from Kumoh National Institute of Technology, Gumi, South Korea, in 2015. He is currently working toward the combined Masters-PhD degree at Ulsan National Institute of Science and Technology, Ulsan, South Korea. His research interests are

Battery Management System and hardware in-the-loop simulation for power management system function testing.



Sangkyu Kwak received the B.S. degree in electrical engineering from Chungnam National University, Daejeon, South Korea, in 2016. His research interests are hardware in-the-loop simulation for photovoltaic modeling and power management system function testing.



Sanghyun Kim received the B.S. degree in the Department of Electronics and Electrical engineering from Pusan National University, Pusan, South Korea, in 2006 and M.S. degree in the Department of Department of Maritime Marine Engineering and Construction from KAIST, Daejeon, South Korea, in 2012. He is currently a Researcher at Hyundai Heavy Industries Co.,Ltd, Ulsan, Korea. His research interests include power, control system and HILS.



Hyungjun Jeon received the B.S. and M.S. degrees in the Department of Electronics and Electrical engineering from Korea University, Seoul, South Korea, in 2007 and 2009 respectively. He is currently a Researcher at Hyundai Heavy Industries Co., Ltd, Gyeonggi-do, Korea. His research interests include power, control system and HILS.



Jeehoon Jung received the B.S. degree in electronic and electrical engineering and the M.S. and Ph.D. degrees in electrical and computer engineering from the Department of Electronics and Electrical Engineering, Pohang University of Science and Technology (POSTECH), Pohang, Korea, in 2000, 2002, and 2006, respectively. From 2006 to 2009, he was a Senior Research Engineer in the Digital Printing Division, Samsung Electronics Company Ltd., Suwon, Korea. From 2009 to 2010, he was a Postdoctoral Research Associate in the Department of Electrical and Computer Engineering, Texas A&M University at Qatar (TAMUQ), Doha, Qatar. From 2011 to 2012, he was a Senior Researcher in the Power Conversion and Control Research Center, HVDC Research Division, Korea Electrotechnology Research Institute (KERI), Changwon, Korea. From 2013 to 2016, he was an Assistant Professor in the School of Electrical and Computer Engineering, Ulsan National Institute of Science and Technology (UNIST), Ulsan, Korea, where he is currently an Associate Professor. His research interests include dc-dc converters, switched-mode power supplies, motor drives and diagnosis systems, digital control and signal processing algorithms, power conversion for renewable energy, and real-time and power hardware-in-the-loop simulations of renewable energy and power grids. Recently, he has been researching high-frequency power converters using wide bandgap devices, smart power transformers for smart grids, power control algorithms for dc microgrids, and wireless power transfer techniques for home appliance applications.