Development of an Operator Training Simulator (OTS) for Marine Power Management Systems

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Synopsis

The complexity of ship controllers has been increasing following the advancements in control devices and technologies as well as the environmental regulations requiring enhanced energy efficiency. Many vessels are under retrofit to integrate onboard Energy Storage System (ESS), necessitating the redesign of the controllers or developing algorithms to improve the vessel efficiency. Operator Training Simulators (OTS) have been developed and manufactured in several industries and have been used for decades. However, the current OTS development method incurs a lot of cost and time for retrofitted vessels with the controller that has changed to accommodate for new technologies algorithms. To develop an OTS that can be flexibly modified for changing the controller of an existing ship, the controller logic, modelling of the physical system, communication protocol, and Graphic User Interface (GUI)-based Human Machine Interface (HMI) should be compatible and consist of reusable model building blocks. In this paper, the logic for each part is designed as a subdivided module, and these modules are made into reusable blocks. As a proof of concept, the OTS for the power management system of an existing LNG carrier ship is developed with the model building blocks and the test results of the main functions of the Power Management System (PMS) are presented.

Keywords: Retrofit; OTS; PMS; Digital Twin; Marine Control Systems; sustainable marine power systems.

1. Introduction

Due to various environment issues, reducing emissions and improving energy efficiency have been the key focus in the maritime industries and logistics industries. The International Maritime Organization (IMO) announced the Greenhouse Gas (GHG) strategy to reduce the carbon intensity of each ship by 70% compared to 2008 and reduce total emissions by at least 50% by 2050 (IMO, 2019). This IMO Initial Strategy states the organization's vision reaffirming the commitment to reducing GHGs from international shipping while continuing efforts to phase GHG out as soon as possible over the century (Joung T.H, 2020).

The IMO published a mandatory regulation of the Energy-Efficiency Design Index (EEDI) in the new ship builds, which is expressed as the grams of CO_2 produced per ship's capacity mile. Existing ships that have been contracted for construction before January 1, 2013, are not subject to EEDI even in 2030, the time when the initial strategic goal is achieved. The Energy-Efficiency eXisting ship Index (EEXI) is a new IMO index for assessing the energy efficiency and environmental impact of ships that have already been put into service (Ivanova G, 2021). It measures CO_2 emission per cargo ton and mile, which is applicable for the existing vessels above 400 gross tonnages (GTs) from 2023 (EEXI, 2021). According to the EEXI calculation formula, which is a technical method, the EEXI value decreases when the ton-mile increases or the carbon dioxide emission decreases in terms of carbon dioxide emissions per ton-mile. In other words, the energy efficiency of ships that emit less carbon dioxide has become the most important factor.

The operational method, Carbon Intensity Indicator (CII) gives each ship an annual rating based on carbon emission efficiency. In other words, while EEXI regulates a ship's carbon emissions with technical equipment such as a shaft or an engine output limiter, CII manages the operation of ships that can minimize carbon emissions (CII, 2021). These regulations influence the ship's abilities such as ship speed. As the speed of ships decreases, more ships will be needed to transport the same amount of cargo within the same period, but it is difficult to secure ships in a short period. Therefore, various methods are being tried to satisfy the regulation, which pushes the development and application of various algorithms in terms of the addition of new equipment or operation, and modification of the controller. As a consequence, new technologies and equipment such as ESS (Energy Storage System) are considered at the design stage, packages such as electric propulsion systems and retrofit of the existing ship's controller to satisfy environmental regulations.

Therefore, it is necessary to develop an OTS that is built quickly and flexibly so that not only new operators but also operators familiar with conventional controllers can get used to the added or changed control functions. In order to develop an OTS that can be flexibly modified for changing the controller of an existing ship, it is

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necessary to configure the logic of the controller, modelling for the physical system, communication method, and GUI-based HMI with compatibility and reusable model blocks. Configuring a simulation structure using reusable models is also a recent need in several industries including maritime such as Open Simulation Platform (OSP) led by ship classification for the digital ecosystem platform. When a digital ecosystem is built, if these digital models are compatible and developed, and configured in a reusable and replaceable type, it can respond more flexibly and quickly to changes (OSP, 2019).

In this study, physical models such as generators and switchboards, local controllers, and IO modules were modelled as subdivided modules, and these modules were made into reusable blocks. Subsequently, the PMS main function was modelled and tested with OTS developed based on these reusable and easily replaceable models. In order to show that the physical model and PMS control logic mounted in this OTS developed for large-scale ships perform technically well, the results of executing the main functions of the Power Management System from the operator's point of view are provided.

2. Operator Training Simulator for Power Management System

The necessity to use simulators for training is increasing in several industries involving complex tasks and hazardous environments (Nazir S, 2015). Training using simulators enables operators not only to train in various environments including potentially hazardous tasks in a safe but also to learn from intended mistakes or accident situations. Moreover, the complexity of control systems has been increasing and it results in facing additional challenges (Passosa C, 2016).

Consequently, it could lead to potential operation errors that may result in disastrous situations. Therefore, the Operator Training Simulator (OTS) that helps operators adapt to the control system and control environment by simulating various situations that may occur as well as the normal state has been of great help. In general, the simulation engine that simulates the dynamic characteristics of the power plant and the software used for controller logic design and verification is different, and the development software for OTS is also different from these in most cases. The configuration software of OTS includes a simulation model or code that simulates dynamic characteristics and a GUI-based HMI that allows the operator to monitor and control the state of the control object through a training environment. Mostly, it takes two to three years to develop the OTS since simulation equipment is expensive, and codes and models are usually not reusable because they are project specific.

In the case of OTS for the Power Management System (PMS), which is the target system of this paper, in addition to the part that simulates the dynamic characteristics of the physical model, PMS logic that works as a remote controller and the local controller required for each system are also modelled and operate them together for OTS to operate similarly to the real system. In this paper, the configuration of OTS is proposed as shown in Figure 1, and as proposed the modularized additional block such as the battery system can be added and interfaced when it is necessary for the vessel to be retrofitted.

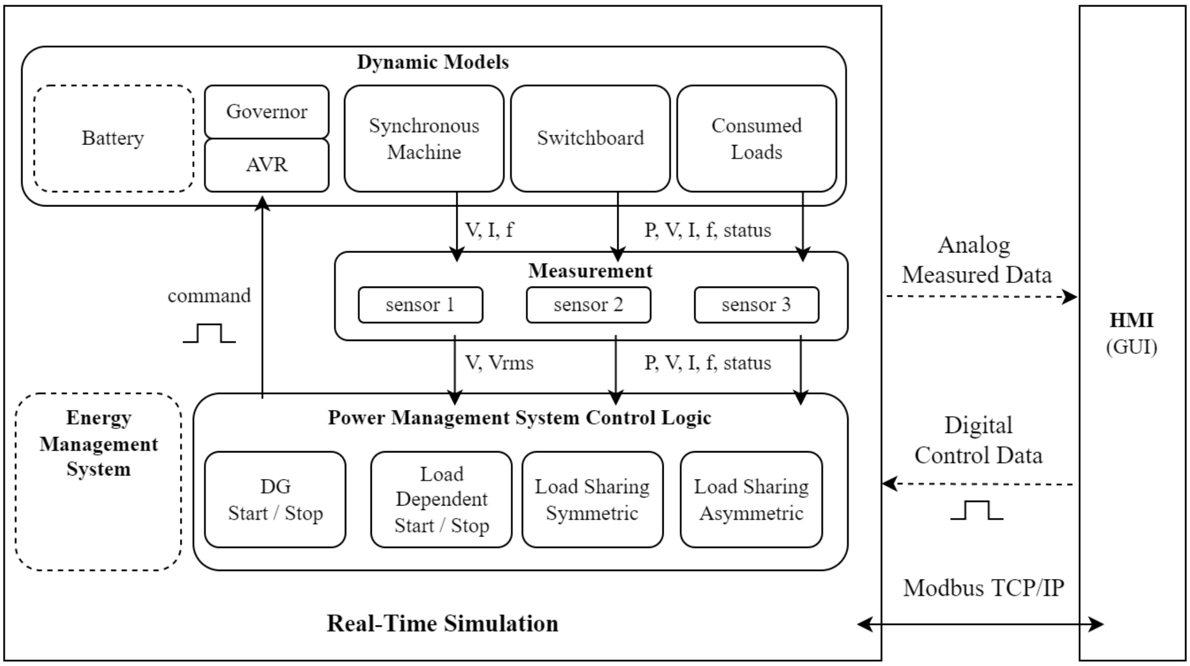

Figure 1: Configuration of Operator Training Simulator

OTS should have the actual controller function, and the target control system in this paper is the PMS which has functions to control and protect the power grid in a ship. The dynamic model of the ship power system is subdivided and modelled, and these physical models are measured in the simulator and transmitted the measured data to the controller. The controller in OTS receives various measured values and digital values to know the status, controls the physical model, and displays information to the operator.

The operator analyses data through GUI-based HMI and sends the command control signals to the controller. The PMS controls a local controller such as a governor to control the physical model based on programmed manual and automatic functions. The physical model, local controller, and controller logic are simulated in real time, and users and operators are configured to train and test on an external GUI-based HMI connected through Modbus TCP/IP. An OPAL-RT, one of the representative high-speed calculation equipment for real-time simulation was used for this simulation platform. These devices ensure real-time in a fixed time step required in the domain for the simulation of physical models. If necessary, a special library is provided to perform parallel computation. In this paper, the OP5700 as a real-time simulation platform was used as shown in Table 1. It allows authenticating the digital models with a small simulation time-step in real-time.

Table 1: OP5700 Features

OP5700 RCP/HIL Virtex7.FPGA-based Real-time simulator – 4 cores
4 CPU cores with 3.46 GHz
Xilinx FPGA: Virtex 7
Real-time OS: Linux Redhat

This configuration provides ease of modification of the entire model, such as when only part of the data of the physical model is changed or when logic is partly changed. In particular, as previously suggested, when other systems are added to the ship system or when logic needs to be changed to improve efficiency, all blocks are subdivided and interlocked so that the model can be replaced easily and quickly unlike the existing OTS. Not only can it be used for OTS, but it also makes it useful in the logic design and test phase. In this paper, the power system such as the ship's generator and switchboard were modelled, and the local controller such as the governor and the Automatic Voltage Regulator (AVR), and measurements such as voltage, frequency and RPM were also modularized and modelled. In addition to sequences of generator start, stop, connect, and disconnect, which are basic control logic of PMS, major functions such as load sharing and heavy consumer start control can all be executed by simulation through OTS.

3. Modelling of Ship Power System

The physical model of OTS demonstrated in this paper consists of 4 generators, 2 main switchboards, and a total of 6 heavy consumers as shown in Figure 2.

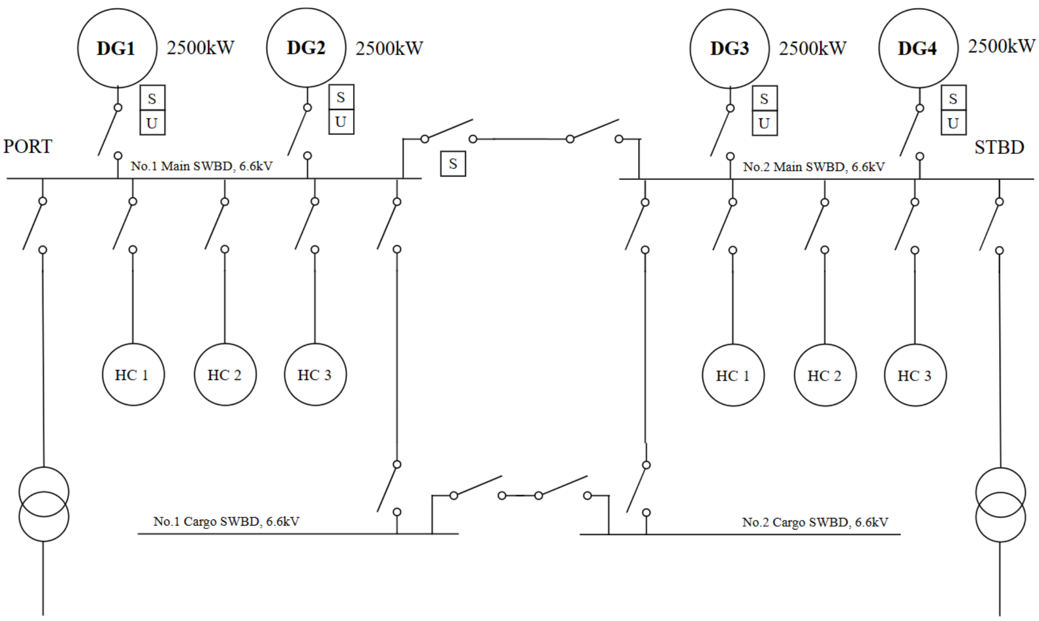

Figure 2: Single Line Diagram of Ship Power System

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The main ship power system consists of two SWBDs, and the main bus-tie connects the two SWBDs. All four generators have the same capacity, and two generators are connected to each main switchboard. There are several heavy consumers (HC) as power consumed loads such as a Low-Duty Compressor (LDC), a Ballast Pump (BP), or a Water Spray Pump (WSP) connected to the main switchboards. As suggested in this paper, each component shown in Fig. 2 is modelled as a module. Each module is divided into subcomponents, i.e. physical model, measurement block, and control block each of which is modelled as a piece. In the following modelling, each component will be presented

3.1. Generator

The generator is operated with a diesel engine governor and an AVR as shown in Figure 3. Part of the dynamic model and measurement is made using the Simscape library of Simulink and the remote controller block is made for working as the PMS.

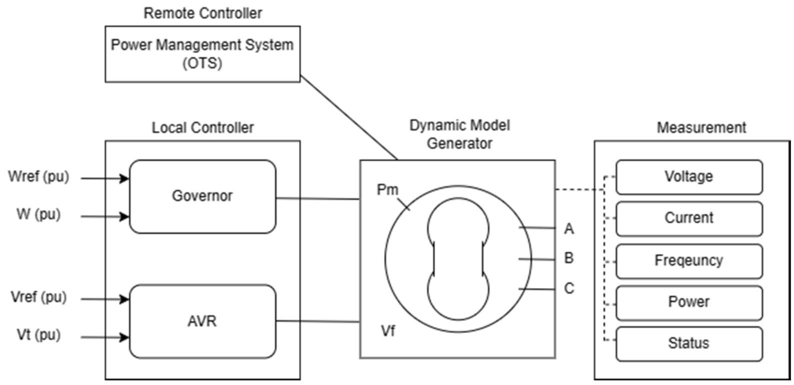

Figure 3: Synchronous Generator and Local Controller Model

The derivation of the equation and modelling process is described in (Krause P.C, 1986). The generator used the sixth order model, and the equations (1) to (3) below represent the generator's stator, and (4) to (6) represent the generator's rotor voltage. The voltage can be expressed as d and q axes using the Park's transformation formula.

$$v_0 = -Ri_0 - \dot{\varphi}_0 \quad (1)$$
$$v_d = -Ri_d - \dot{\varphi}_d - \omega\varphi_q \quad (2)$$
$$v_q = -Ri_q - \dot{\varphi}_q - \omega\varphi_d \quad (3)$$
$$v_f = R_f i_f - \dot{\varphi}_f \quad (4)$$
$$0 = R_D i_D - \dot{\varphi}_D \quad (5)$$
$$0 = R_Q i_Q - \dot{\varphi}_Q \quad (6)$$

The subscripts 0, d, and q denote the neutral point and the d-axis and q-axis, respectively, and f, D and Q, denote the field component, the d-axis component, and the q-axis component of damper winding, respectively. In Figure 3, the output of the governor is mechanical power called Pm in the model to rotate the generator rotor. Electric power is generated by controlling the governor. Wref(pu) means the reference speed for the rotor of the generator to rotate at the specified speed. W is the measured rotor speed from the generator. The governor adjusts the rotor speed with the difference in the input values by controlling the fuel rack position.

AVR is a device that automatically compensates for fluctuations in generator terminal voltage due to load speed fluctuations and keeps them precise and constant by controlling field voltage in the rotor. AVR model has two inputs which are reference voltage (Vref) to maintain the terminal voltage in the rated voltage, and the terminal voltage (Vt) measured from the generator. The AVR block calculates the field voltage from the difference between the inputs (IEEE, 2016).

3.2. Switchboard

One of the main elements of a power distribution system is the main switchboard. It is basically designed to distribute the power from the generators for all normal operating conditions. In this configuration, the ship power systems have two main switchboards and two main cargo switchboards. They are connected between generators and power consumed loads through several circuit breakers. Those circuit breakers are controlled through the HMI of OTS by operators in REMOTE mode. A switchboard has several sensors such as voltage, current, and frequency so that it can trip the circuit breakers when the under-voltage or the reverse current situation happens. In this system, the switchboard was modelled including the synchronizer function for generators to be synchronized when they need to be operated in parallel and let the incomer circuit breakers closed when synchronized. The condition for synchronization is as shown in Figure 4.

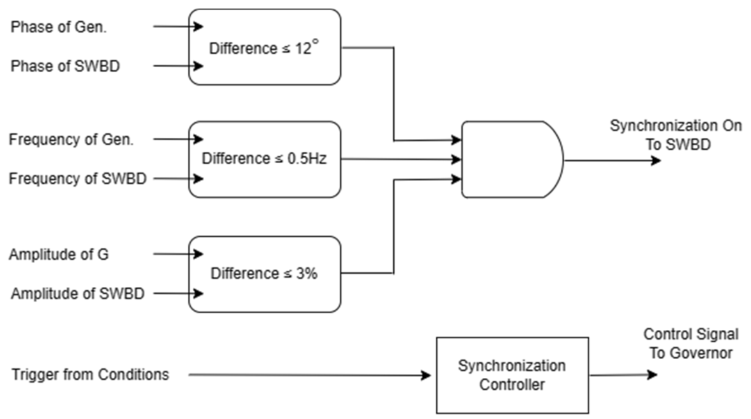

Figure 4: Logic Diagram for Synchronization of Generators

The generator voltages must be synchronized when they are connected to the same grid for the parallel operation. Therefore, the synchronization module should be modelled as well because it is not the role of the PMS. The amplitude, frequency, and phase of the generator voltage should be the same before the generators in the parallel operation are connected. 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 0.5Hz (Salcedo R. O, 2016) as shown in Figure 4. Before the parallel operation, the PMS gives the circuit breaker close command to connect generators. The generator circuit breaker should not be closed before receiving the synchronization signal even if the PMS sends the close command signal. In addition, the switchboard performs important roles such as net current calculation, net frequency calculation, and load sharing through PMS control.

4. Power Management System (PMS)

The PMS that manages the efficient power management, blackout prevention, and recovery of ships is one of the main systems. Figure 5 shows the main functions of PMS to control the switchboard and generator with command and feedback signals.

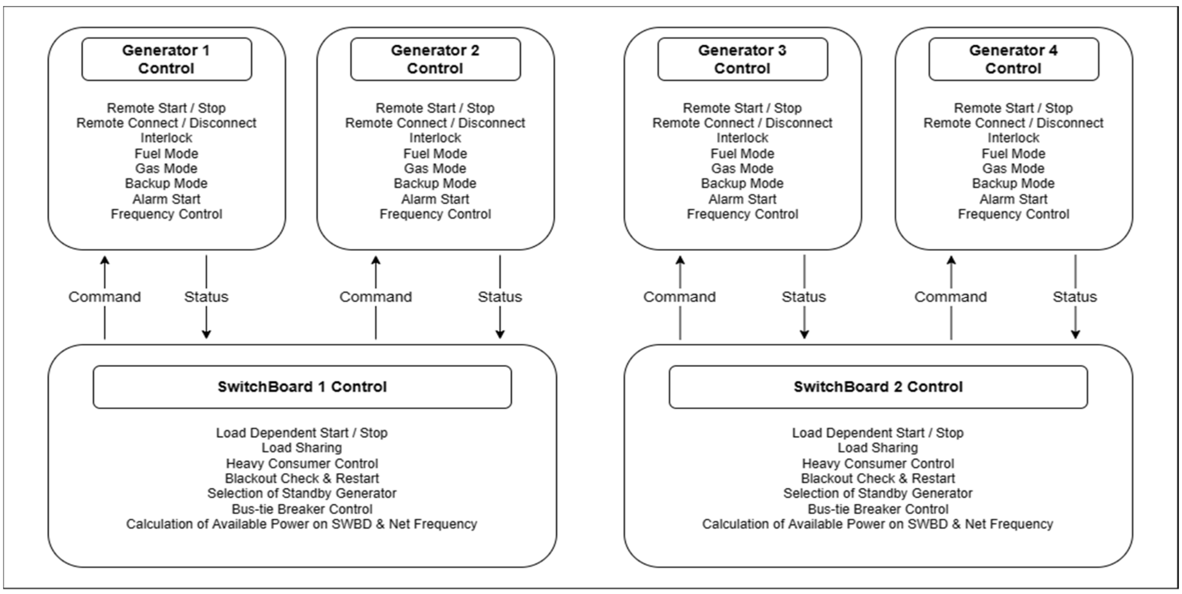

Figure 5: Main Functions of Power Management System

The PMS can be a control module of the Integrated Automation System (IAS) to control generators, switchboards, and heavy consumers to manage and protect the ship grid. The primary function of the PMS is to ensure that the load does not overload the whole switchboard capacity based on the control logic such as load dependent start and blackout recovery, even if a generator shut down unexpectedly (Henryk P., 2019).

4.1. Generator Control and Monitoring

In this system, four diesel generators were modelled, and PMS has several main control functions as followed in Table 2 and the OTS should be implemented the same as the PMS.

Table 2: Main Control Functions of PMS

Remote Generator Start / Stop manually
Automatic Start the Standby Generator
Standby Selection
Remote Generator Breaker Connect / Disconnect

When the control mode is set to Local, the prior control authority is at the Local controller, and when the mode is set to Remote, the PMS takes the control for generators to start and stop. The generator can be started according to the following sequences as shown on the left of Figure 5.

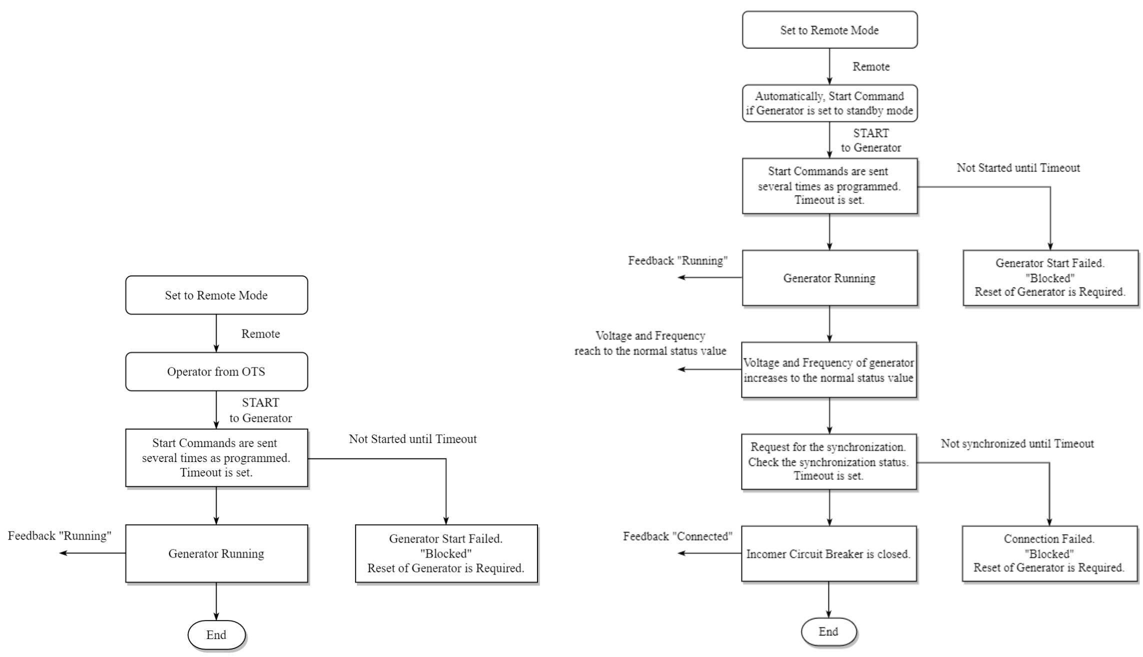

Figure 6: Flow Chart for Remote Start / Stop Sequence: Manual (left) & Automatic (right)

The right of Figure 6 shows the Automatic start and stop sequence. When the control mode is set to Remote and the automatic start request is sent by the PMS, the higher priority generator is started in conditions such as the start from the dead bus, load dependent start, and heavy consumer start request.

4.2. Switchboard Control and Monitoring

There are several circuit breakers such as bus-tie breakers, incomer circuit breakers, and others for heavy consumers and common loads. Bus-tie circuit breakers basically consist of a master circuit breaker and a slave circuit breaker. PMS controls only the master circuit breaker. The switchboard has internal logic to ensure the correct phase angle when the close command signal is received. When PMS opens the bus-tie circuit breaker, the switchboard opens the master and slave circuit breaker at the same time.

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Table 3: Main Control Functions of Switchboard

Bus-tie Breaker Operation
Circuit Breaker Protection
Load Dependent Start / Stop
Heavy Consumer Start Control
Load Sharing (Symmetric, Asymmetric, Fixed & Manual)
Blackout Restart

In this study, load dependent start / stop and load sharing sequences will be represented and implemented using the developed OTS. Load dependent start sequence is performed based on Table 4 and those parameters can be changed for each control system, ship scale, and situation.

Table 4: Parameters for the Load Dependent Start / Stop

No. of Gen. connected	Start Limit 1	Delay Time 1	Start Limit 2	Delay Time 2	Stop Limit	Delay Time
1	85 %	120 seconds	90 %	10 seconds	-	-
2	85 %	120 seconds	93 %	10 seconds	70 %	15 minutes
3	90 %	120 seconds	95 %	10 seconds	75 %	15 minutes
4	-	-	-	-	80 %	15 minutes

For example, when only the first generator is running and connected to the switchboard, and the load reaches 85% and stays for 120 seconds, the standby generator will be started and connected in parallel automatically. Operators can set those parameters based on their control philosophy on this developed OTS. Load sharing mode in PMS mostly four kinds of modes to have load shared to each generator, which are Symmetric mode, Asymmetric mode, Fixed mode, and Manual mode shown in Table 5.

Table 5: Load Sharing Modes

Symmetric mode	Load shared equally on running generators. e.g., 2 generators, 50%:50%
Asymmetric mode	Load shared asymmetrically based on a set point on each generator e.g., 2 generators, 20%:80% normally
Fixed mode	Operators set the parameter of fixed power on a generator The generator supplies the fixed power, the others take the rest.
Manual mode	Operators control speed control order directly on PMS The generator supplies the power from the operator's order

5. Simulation results of implementing the OTS

In this section, the OTS is demonstrated for a PMS with four equal capacity generators, two main switchboards, and loads. A load profile was applied according to the table defined for the set-point parameters and time to test PMS main functions. The sequence and logic for generator start/stop, circuit breaker closed/open locally and remotely should be modelled and work correctly explained above to control generators and switchboards. Therefore, in this study, load dependent start and symmetric load sharing sequences of OTS are tested. Additionally, the fixed load sharing sequence is also tested. Dynamics such as pulse width from the OTS, the time to build the voltage and frequency of the generator, and the time to trip the circuit breaker can be appropriately adjusted according to the parameters of each system or OTS.

A. Load Dependent Start and Symmetric Load Sharing

Test Scenario:

Action	***Event***
prerequisite	All generators & All circuit breakers are set to REMOTE All generators are set to Symmetric Mode for load sharing G1 is running and connected G3 is stopped and set as standby 1 Load Dependent Start Control activated on OTS
Manual	Increase load until reaching to 90% and staying for 10 sec described in Table 3
Expected Result	G3 will be started and connected automatically G1 and G3 take each half of the total load symmetrically
	Sequence completed within defined time, and no control signal from OTS

The result for the load dependent start and symmetric load sharing sequence of OTS is shown in Figure 7. The operator sets the load dependent start and stop control activated on the OTS. The first generator started with the start command in red and took the increasing load until reaching the set point, 90% at 11 seconds, and supplying power for 10 seconds. The OTS got the second generator, G3 that is set to standby no.2 started at 21 seconds with the start command in purple and tried to control both generators based on symmetric load sharing sequence and it was completed within 1 minute.

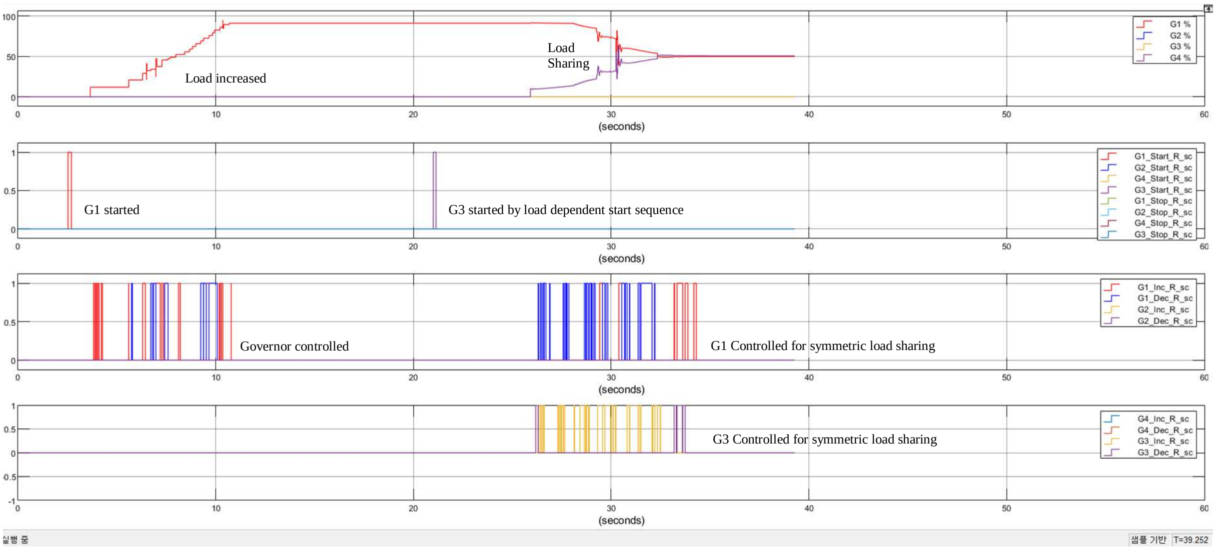

Figure 7: Result of Load Dependent Start and Symmetric Load Sharing

B. Load Dependent Stop and Reducing Load

Test Scenario:

Action	***Event***
prerequisite	All generators & All circuit breakers are set to REMOTE All generators are set to Symmetric Mode for load sharing G1 and G3 are running and connected G3 is set as standby 1 Load Dependent Stop Control activated on OTS Total load is set to above 90%
Manual	Decrease load until reaching under 70% described in Table 3
Expected Result	G3 will reduce load, stop, and be disconnected automatically G1 will take all load
	Sequence completed within defined time, and no control signal from OTS

The result for the load dependent stop and reducing load sequence of OTS is shown in Figure 8.

The operator set the load dependent stop control activated on the OTS. Two generators started in sequence and took load symmetrically. Load started to decrease at 33 seconds gradually until reaching the set point. The OTS tried to control the second generator to reduce load before stopping and disconnecting G3. The OTS disconnect the second generator at 44 seconds when the load on the second generator was under 8%, and the first generator took the rest of the load from the second generator.

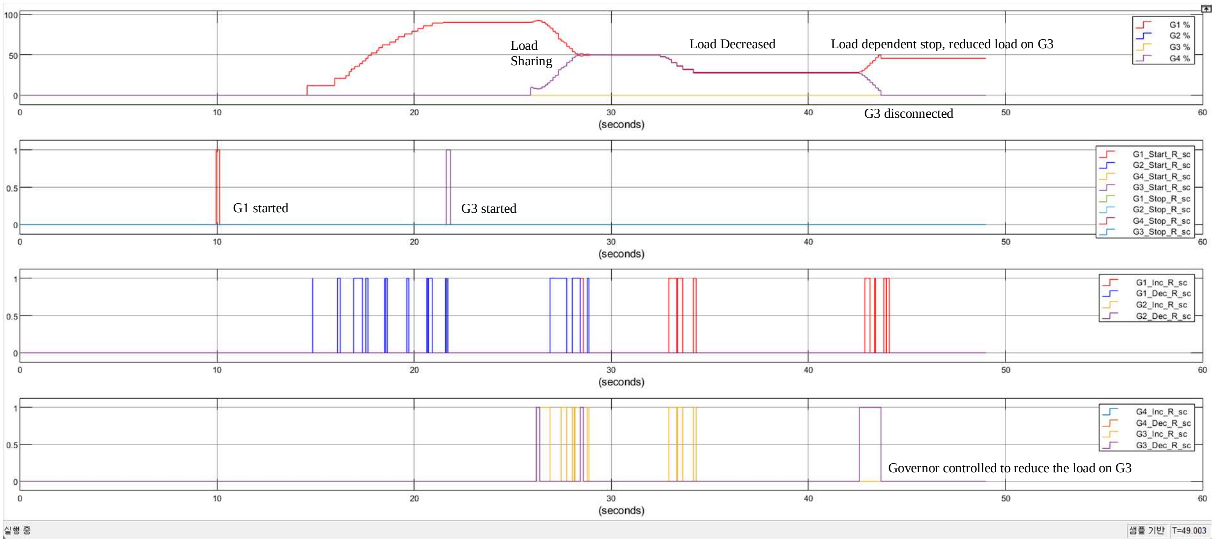

Figure 8: Result of Load Dependent Stop and Reducing Load

6. Conclusions

In this paper, the development of an OTS for a large-scale marine power management system, including the ship power system such as generators and switchboards, and the related local controller was presented. The proposed OTS can reduce the cost and time necessary to retrofit the ship controller or change the algorithm due to environmental regulations such as EEXI or CII. The methodology was modularization of each sequence of PMS and dividing digital models into individual control modules. All these small models work interconnected within a real-time simulation platform for OTS. The test scenarios focused on testing that can demonstrate some of the main functions of PMS by combining them at a time. Based on these results, the presented OTS showed that it is suitable for operators to test and train the main functions of PMS for real ship operation. This could help the operators operate the vessel with a more advanced control system and with the renewable-energy power system such as batteries and hence assisting to reduce the emissions to meet the environmental regulations. Since the models can be modified and reused, they can also be used for verification of control logic or design control algorithm. This approach is also suitable for the simulation environment trend for co-simulation and model exchange, as expressed in a co-simulation platform such as OSP in recent years.

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