Modelling of a Shipboard Electric Power System for Hardware-in-the-Loop Testing

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***Abstract*—As the design complexity of modern maritime systems is increasing, the need for advanced and appropriate simulation technologies is higher than ever. Different subsystems such as shipboard power systems and maritime controllers are directly interlinked making system integration and testing a challenging task. Hardware-in-the-Loop (HIL) testing is an advantageous methodology used for the systematic testing of control systems regarding correct functioning, performance and reliability.**

In this work, we present a HIL testing methodology to verify a ship power management system (PMS). For this, an AC shipboard power system is modelled including all relevant components such as diesel engines, generators, circuit breakers and loads interfaced by the PMS. The model also includes local controllers like speed governors and automatic voltage regulators (AVRs). A functional PMS was developed and implemented emulating the behaviour of a real controller. The models are exported as Functional Mock-up Units (FMUs) which represent stand-alone simulators. As HIL testing testbed the Open Simulation Platform (OSP) environment is used. This standardized and open platform enables co-simulation and also provides HIL testing capabilities. The exported FMUs are connected via the OSP environment. A load-dependent start-stop scenario is carried out to validate the correct functioning of the PMS and the test setup.

***Index Terms*—Ship Power System Modelling, Power Management System, Hardware-in-the-Loop, Open Simulation Platform (OSP), Digital Ship**

I. Introduction

As a response to stricter environmental regulations and an ever-increasing demand for higher energy efficiency, the maritime industry increasingly relies on hybrid and electric power system for vessels [1], [2]. The use of energy storage systems (EES), new energy sources and digital technologies enables increased efficiency and reliability as well as a low-emission operation of both newly built and retrofitted vessels [2]. At the same time, the extensive use of these technologies increases the complexity and interdependence of shipboard power systems and controllers such as power management systems (PMS) and energy management systems (EMS).

As a result, the integration, testing and verification of marine control systems becomes a challenging task comprising numerous risks [3], [4], [5]. Early and continuous integration of both hardware and software is eligible, but it is common to perform the integration and the main testing of the vessel's power and control system late in the shipbuilding process and during sea trials [6]. Since prototypes are costly, both hardware and software systems are often not available for testing and verification. Modern modelling and simulation approaches such as digital twin and Hardware-in-the-Loop (HIL) simulation cope with these challenges while reducing risks and costs [5].

Recent research has shown that HIL simulation is an appropriate and advantageous methodology for testing and verification of maritime control systems [3], [4], [5], [6], [7]. HIL testing is performed on a real-time capable digital replica of the real hardware while the controller under test remains the original one. Therefore, HIL testing is not depended on the operational safety limits and the availability of a real system [4], [5]. This facilitates more extensive, flexible and cheaper testing.

Modern control systems are becoming more complex and coupled with numerous systems resulting in an high interdependence between different hardware systems. Therefore, a simulation platform integrating all hardware systems affected by the controller is beneficial. Some research on HIL combined with co-simulation has shown that this approach can be beneficial for testing highly integrated maritime systems [8], [9]. Extending this concept, the Open Simulation Platform (OSP) has been established to provide a collaborative and standardized ecosystem to preform co-simulation including HIL testing [10].

In this work, a HIL simulator platform based on the OSP co-simulation environment is developed to test and verify a ship power management system. A digital replica of a ship power and propulsion system is modelled and exported as Functional Mock-up Unit (FMU), a stand-alone simulator. Also, the PMS is implemented as an FMU and interfaced to the power system via the OSP environment. Several simulations are carried out to prove the correct functioning of the PMS and the HIL simulator. It is shown that the OSP environment can serve as a platform for HIL testing including co-simulation and real controllers can be integrated based on the Functional Mock-up Interface (FMI) standard [8].

II. Hardware-in-the-Loop Methodology

The Hardware-in-the-Loop approach is used for the development, testing and verification of control systems. This methodology is well-establish in industries such as automotive, aviation and aerospace and is increasingly important for the maritime industry as modern vessels become more complex [3].

The main principle of the HIL methodology is that the input/output (I/O) communication between the real hardware (e.g. sensors, actuators, dynamic systems) is replaced by the signals of the HIL simulator. The HIL simulator mimics the behaviour of the hardware that is initially interfaced by the controller. From the controller's perspective, there is no difference between the I/O signals of the real and the emulated hardware system [4], [6].

A HIL simulator is a real-time simulator consisting of a virtual plant (the mathematical model of the system to be replaced), peripheral equipment (simulated actuators and sensors) to interface the controller through the I/O communication channels as well as hardware and software to perform the simulation [3]. The real system and the conceptual setup of HIL testing are shown in Fig. 1.

To develop an appropriate simulator and to define the correct test scope, the knowledge about the inner working of the controller is not necessary. Instead, the detailed functioning in terms of functions, design philosophy and I/O interfaces of the controller is indispensable [4]. Moreover, an appropriate level of accuracy and fidelity of the mathematical model is important to ensure the same behaviour as the real system.

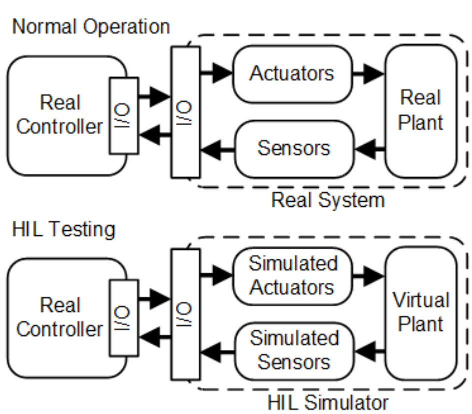

Fig. 1. Real system and conceptual setup of HIL testing [4]

III. Shipboard Power System Modelling

The single line diagram (SLD) of the implemented AC ship power and propulsion system is shown in Fig. 2. The power system consists of two main switchboards, each of which is supplied by a diesel-fuelled synchronous generator. A bus tie breaker connects and disconnects the switchboards.

The main loads of the power system are the two propulsion drives consisting of an induction machine fed by an AC/AC power electronic converter. Consumers such as cargo pumps, winches and hotel loads are subsumed as electrical loads. All generators and appliances are connected to the switchboards through circuit breakers. Additionally, local controllers such as speed governors and automatic voltage regulators (AVRs) are implemented into the power system.

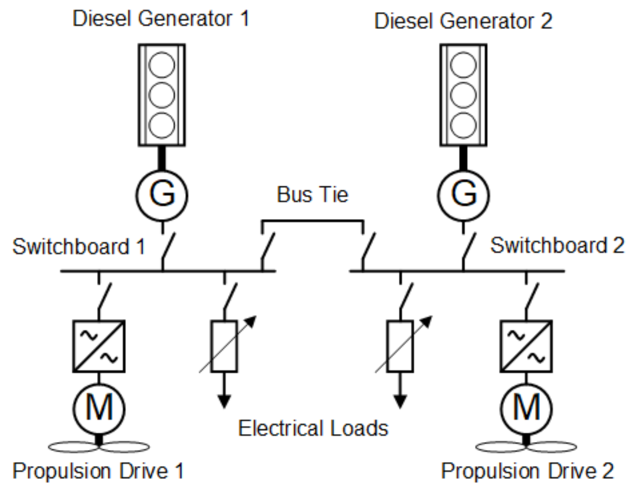

Fig. 2. Single line diagram of the ship power and propulsion system

The power system is simplified compared to an actual ship power system but consists of all power components needed to validate the main functions of a typical power management system. To provide communication between the power system and the PMS an I/O interface is included in the model. This interface transmits the signals of the simulated sensors and receives the control signals of the PMS. The control signals directly affect the power system simulation which leads, for example, to changing conditions of the circuit breakers and generators.

The power system model was implemented in MATLAB/Simulink and exported as a Functional Mock-up Unit. The FMU constitutes a stand-alone simulator that can be connected to the PMS via the Open Simulation Platform co-simulation environment. The communication between the PMS and the power system simulator is established by an I/O-interface matching the input and output signals of both systems.

A. *Diesel Generators*

The diesel engines are modelled as torque generators given by the following transfer function based on [11]:

$$T_m(s) = \frac{k_y e^{-\tau s}}{1 + \tau_c s} Y(s) \quad (1)$$

T_m is the generated torque by the engine and $Y(s)$ is the fuel index. k_y is the engine gain, τ is the time delay equal to half the period between consecutive cylinder firings and τ_c represents the time of the torque build-up from cylinder firings:

$$\tau_c \approx \frac{0.9\,[rad]}{n} \quad (2)$$

where n is equal to the speed of the engine. The torque balance of the shaft is as following:

$$J_m \dot{n} = T_m - T_e - T_f \quad (3)$$

where J_m is the summed up inertia of the diesel engine, the generator and the shaft. $\dot{n}$ is the shaft acceleration, T_e is the electromagnetic torque of the generator and T_f is the friction torque.

The generators are modelled as 3-phase salient pole synchronous machines. The electrical part equals a sixth-order state-space model in the dq-reference frame.

B. Switchboards and Circuit Breakers

The switchboards are implemented as simple connection lines assuming no relevant dynamics. The circuit breakers are modelled as switches which have a resistance of 1 MΩ in open condition and a resistance of 10 mΩ in closed condition.

C. Electric Propulsion Drives

The asynchronous machines are implemented as 3-phase squirrel cage induction machines in the dq-reference frame whereat the electrical part equals a fourth-order state-space model. The machine is fed by an AC/AC converter consisting of a six-pulse diode rectifier and a two-level inverter using IGBTs.

The propulsion drive is controlled by a direct torque controller with space vector modulation (DTC-SVM) as shown in Fig. 3. In this approach, the magnetic stator flux ψ_s and the electromagnetic torque T_e of the induction machine are estimated based on the stator current I_s and the stator voltage V_s. The estimated values are compared with the flux reference ψ_{ref} and the torque reference T_{ref} respectively. Based on the error values, the PI controllers and a SVM logic calculate the appropriate switching pattern of the inverter that minimizes both flux and torque error.

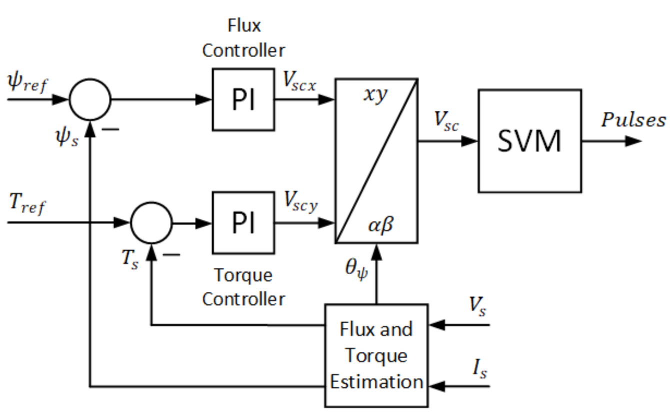

Fig. 3. Control scheme of the implemented direct torque controller using space vector modulation (DTC-SVM)

D. Main and Hotel Loads

The main and hotel loads are implemented as 3-phase dynamic loads capable to represent both active and reactive power consumers.

E. Local Controllers

The speed of the diesel engine and thus the power system frequency are controlled by a speed governor derived from [11]. The governor is a PI controller including an anti-windup in the integration part and adjusts the engine's fuel index Y as a function of the reference speed n_{ref} and the measured speed n_m:

$$\dot{Y}_i = \frac{k_r}{\tau_i}((n_{ref} - n_m) - K(Y_{PIb} - Y_{PI})) \quad (4a)$$

$$Y_{PIb} = Y_i + k_r(n_{ref} - n_m) \quad (4b)$$

$$Y = min(max(Y_{PIb}, Y_{lb}), Y_{ub}) \quad (4c)$$

where k_r is the governor gain, τ_i is the PI time constant, K is the anti-windup gain and Y_{lb} and Y_{ub} are the lower and the upper bounds for the integration part of the governor.

The terminal voltage of the generator is controlled by an AVR setting the excitation voltage V_f of the generator as a function of the reference voltage V_{ref} and the measured voltage V_m. The AVR is also implemented as PI controller including an anti-windup in the integration part, compare (4).

IV. Power Management System Modelling

A power management system provides high-level control of the ship power system and ensures that power capacity and power demand of the vessel are aligned at any time. The PMS is interfaced with the ship power and propulsion systems and controls the power components based on sensor and user input signals.

The implemented PMS provides several functions which are presented in the following [2]. The PMS including an I/O communication interface was developed in MATLAB/Simulink and exported as FMU to be connected to the OSP co-simulation environment.

A. Generator Synchronization

Before a generator can be connected to a running power system or a bus tie between live bus bars can be closed, the systems have to be synchronized. For this, parameters such as waveform, phase sequence, voltage magnitude, frequency and phase angle of both systems have to be matched. The implemented synchronization module (Fig. 4) monitors the relevant voltages and adjusts the reference speed of the governor to match the frequency and the phase angle of the systems to be connected. To match the voltage magnitude, the PMS adjusts the reference voltage of the AVR. The waveform and the phase sequence are given by the implemented power system.

If the mismatch of the parameters is within an acceptable range, the PMS sends a close signal to the circuit breakers and the synchronization process is completed. The speed and voltage reference values of the governor and the AVR are no longer influenced by the synchronization module and the load dispatch of the generators can be readjusted.

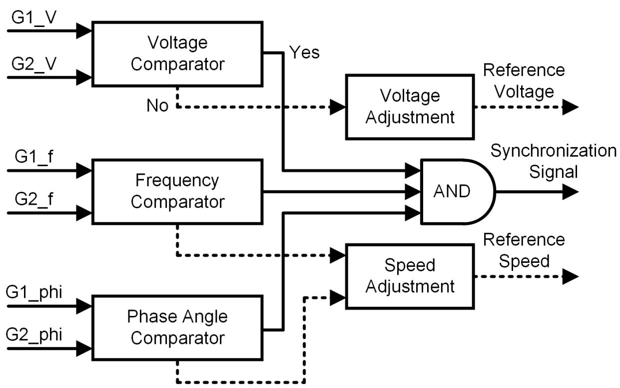

Fig. 4. Simplified scheme of the synchronization module

B. Active and Reactive Power Load Sharing

In parallel operation of two or more gensets, an appropriate load sharing approach is needed to maintain the stability of the ship power system. Hence, a frequency droop controller and voltage droop controller are implemented into the PMS. The active power load-sharing is realized by adjusting the reference frequency f_{ref} of the governor as a function of the measured actual active power load P_m of a generator:

$$f_{ref} = f_0 - K_{Pf}(P_m - P_0) \tag{5}$$

where f_0 is the base frequency, K_{Pf} is the active power sharing factor and P_0 is the base active power. Reactive power load-sharing is realized by adjusting the reference voltage V_{ref} of the AVR as a function of the measured actual reactive power load Q_m:

$$V_{ref} = V_0 - K_{QV}(Q_m - Q_0) \tag{6}$$

where V_0 is the base voltage K_{QV} is the reactive power sharing factor and Q_0 is the base reactive power.

C. Load-dependent Start-Stop of Gensets

To ensure a sufficient power capability at any time, the PMS constantly monitors the power capacity of the running generators and the power consumed by the loads. If the total available power falls below a predefined setpoint for a specific time, the next generator in start sequence will be started, synchronized and connected to the power system. If the available power exceeds a certain threshold for a specific time the generator will be disconnected and stopped to save fuel and to protect the diesel engine [12].

D. Blocking of Heavy Consumers

To protect the power system from overloading, the starting of heavy consumers such as propulsion drives and cargo pumps will be blocked unless the available power is sufficient. According to the start sequence, the PMS starts additional generators and connects them to the power system as long as the load demand of the heavy consumer can be covered. When the needed power is available, the PMS sends an ”available” signal and the corresponding circuit breaker can be closed.

V. Power Management System Verification

To test and verify the PMS, the Open Simulation Platform (OSP) is used as HIL testing environment. The goals of OSP are to create a maritime industry ecosystem for co-simulation and managed sharing of “black-box” simulation models [13]. The simulation environment is building on the FMI standard for co-simulation and enables the integration of maritime-related models from different engineering domains such as hydrodynamics (hull, waves) or mechanics (cranes). Establishing a digital replica or a digital twin of a ship, this approach enables a full-system simulation that can be used throughout the life cycle of a ship.

The OSP environment also allows integrating HIL testing within the co-simulation approach. Real controllers such as a PMS can be interfaced by a communication FMU routing the I/O-signals between the controller and the OSP environment. In this case, the OSP environment is simulating the real system and can be considered as a HIL simulator. The combination of co-simulation and Hardware-in-the-Loop testing has been shown by [8].

To test and verify the test platform and the correct functioning of the PMS, a representative load-dependent start-stop scenario is carried out. In contrast to a typical HIL testing setup, in this work also the real PMS controller is replaced by a model (section IV).

A. Setup of the Hardware-in-the-Loop Simulator

The models of the power system, the diesel generators and the PMS are exported as stand-alone FMUs, adhering to the FMI 2.0 standard, by utilizing an external MATLAB toolbox. The most important model parameters are given in Table I.

TABLE I
MODEL PARAMETERS

Component	**Parameter**
Genset	4600 kVA, cos$\varphi = 0.8$, 6.6 kV_{RMS}, 720 rpm, 10 poles
Switchboard	6.6 kV_{RMS}, 60 Hz
Loads	3-phase dynamic loads
Frequency Droop	Droop rate = 2 %, f_0 = 61 Hz, P_0 = 0 MW

The test setup of the HIL simulation is shown in Fig. 5. The FMUs of the power system, the diesel engines and the PMS are connected to the FMI co-simulation interface. The routing of the signals between the FMUs is performed by a master algorithm which is part of the OSP environment. A scenario manager sends predefined signals to the FMUs thus representing e.g. changing loads or the input by a user.

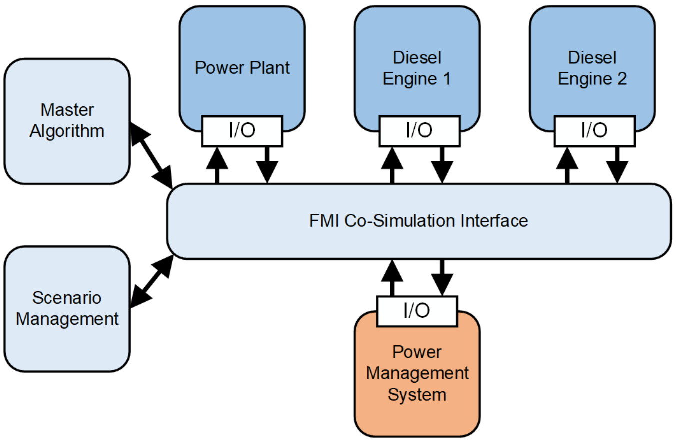

Fig. 5. Test setup using the OSP co-simulation environment as HIL simulator

B. Test Scenario

To validate the correct functioning of the PMS and the OSP setup, a representative load-dependent start-stop test scenario is carried out. In this test, the PMS ensures that the optimal number of generators n is connected to the power system to supply the loads at any time. The simulation is performed for 400 s and the events are given in Table II.

Initially, only one generator is connected to the power system. If the average power of the generator P_{avg} falls below a predefined value $P_{avg,H}$ for a specific time τ_H, a second generator is started and connected to the grid thus increasing the online power capability of the system. If the average load of both generators exceeds a threshold $P_{avg,L}$ for a time τ_L, the second generator is disconnected again to reduce fuel, emissions and operation time. Table III shows the conditions for starting and Table IV for stopping a second generator. The parameters should be adjusted regarding the expected load profile of the ship.

TABLE II
SIMULATIONS EVENTS

Time	**Event**
0 s	Genset 1 started
28 s	Genset 1 connected to switchboard
29 s	Load circuit breakers closed
32 s	Total load set to 2.5 MW Timer for load-dependent start initiated
62 s	Timer $\tau_H = 30\ s$, genset 2 started
92 s	Genset 2 synchronized and connected to switchboard
150 s	Total load set to 6 MW
224 s	Total load set to 1.8 MW Timer for load-dependent stop initiated
344 s	Timer $\tau_L = 120\ s$, genset 2 stopped

TABLE III
LOAD-DEPENDENT START TABLE

n	$P_{avg,H}$	τ_H
1	60 %	30 s
2	-	-

TABLE IV
LOAD-DEPENDENT STOP TABLE

n	$P_{avg,L}$	τ_L
1	-	-
2	25 %	120 s

C. Simulation Results

To verify the load-dependent start-stop functionality, the simulations is performed according to the simulation events given in Table II. The standby sequence of the generators is {genset 1, genset 2}, where genset 1 is running during the whole simulation. The total load, the load-dispatch and the online power capacity are shown in Fig. 6. The connection status of the generators is presented in Fig. 7 and the status of the timers is shown in Fig. 8.

The simulation results match with the expected behaviour of the PMS. Genset 1 starts and is connected to the grid providing a specific power capability. The total load exceeds the preset load limit and a timer starts counting. Reaching the delay τ_H, the second generator starts, is synchronized and connected to the grid increasing the online power capability. Now, both generators run in parallel and the droop controllers adjust the speed reference of the diesel engines to share the load equally. When the total load falls below a specific value, another timer starts counting. Reaching the delay τ_L, the second generator is disconnected and stops. Finally, generator 1 supplies the total power.

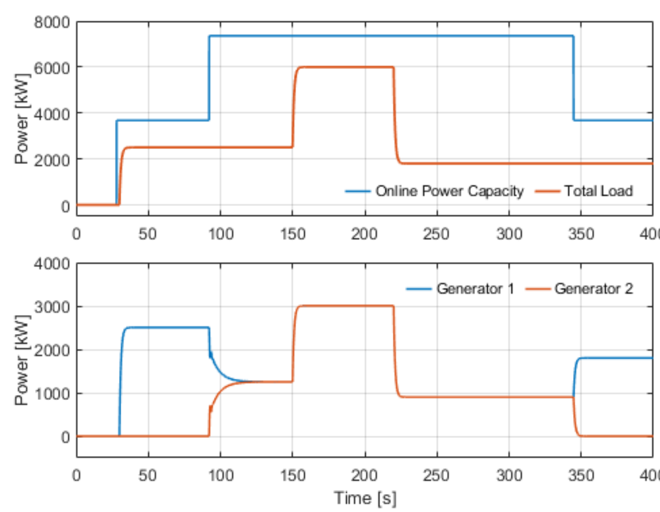

Fig. 6. Total load and online power capacity of the power system, load-dispatch between the generators

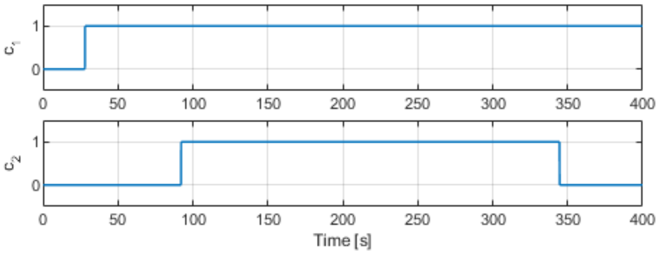

Fig. 7. Connection status of the gensets (1 ≙ connected, 0 ≙ disconnected)

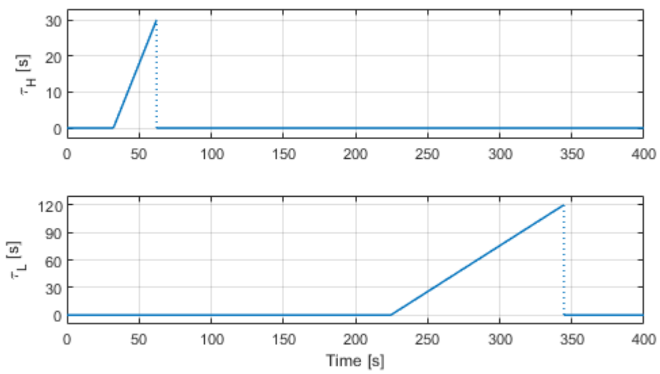

Fig. 8. Timer status high (τ_H) and low (τ_L)

VI. Conclusion

In this work, a shipboard AC power system including local controllers has been modelled and exported as Functional Mock-up Unit. The developed model was used to test and verify a ship power management system following the Hardware-in-the-Loop testing approach. As HIL simulator, the Open Simulation Platform environment was used. The PMS controller was emulated by a dedicated stand-alone simulator and interfaced with the power system model. A representative simulation validating the load-dependent start-stop functionality of the PMS was carried out.

It has been shown that HIL testing is an appropriate methodology to test and verify complex maritime control systems. HIL testing is performed in a virtual test bed built on a virtual model of the actual hardware system. Due to this, the reliability of the test results also depends on the model accuracy and fidelity. At the same time, the virtual test bed enables the control system to operate in both normal and off-design condition without damaging any hardware system. The beneficial use of the Open Simulation Platform environment for co-simulation including HIL testing has been demonstrated.

Further research is needed on the real-time capability of the power system models and the Open Simulation Platform as HIL simulator. Also, a real PMS controller should be interfaced to the OSP environment to demonstrate its connectivity.

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