Co-Simulation of a Marine Hybrid Power System for Real-Time Virtual Testing

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Abstract—**Co-simulation enhances the efficient simulation development even for complex systems reducing time to market and computational effort. This work aims to develop a marine hybrid power system simulator using a co-simulation approach. The subsystems are packed as Functional mock-up units (FMUs) with the standard interface called functional mock-up interface (FMI). The FMUs for major subsystems are generated from the previously developed dynamic system model. However, FMUs developed by the partners are also compatible for the implementation. These FMUs are implemented in an open simulation platform's (OSP's) software Kopl and Co-Sim App to develop a system simulator. The use of a co-simulation framework for real-time virtual testing and various model fidelity implementation is studied. The developed simulator is used for testing the functionalities and operational capabilities of the studied system. It can simulate faster than real-time, thereby enhancing its use for real-time virtual testing applications. Implementing various fidelity FMUs enhances modularity. It also increases the flexibility in an FMU selection based on the simulation objectives, accuracy, and computational effort.**

I. INTRODUCTION

Ship hybrid power systems help achieve the emission reduction and efficiency improvement targets set by the regulatory authorities [1], [2]. However, the implementation of advanced technology such as hybridization also increases the complexities in the power system. To design, test, operate, and train such complex systems in a cost-effective and risk-free environment, modeling and simulation can be an effective tool [3], [4].

Unlike automobile industries, the ship power and propulsion systems are usually one-of-a-kinds. Although the components and subsystems are often modular, the system as a whole is usually unique. It results in the various configurations of the power and propulsion systems, making them impractical for mass production. Similar is the case for the simulator development for the maritime systems. Proper modeling of the ship systems requires significant time and effort. Besides, various components and systems in multiple energy domains and different dynamics or system time constants complicate the simulator development process [5].

A mathematical model developed by the component or system provider retains the necessary expertise and essential knowledge. Therefore, it is beneficial if they can provide its digital or mathematical representation with standard interfaces, compatible with other interconnected systems, as in a real ship. Usually, expertise is domain-specific. An expert in hydrodynamics may not be equally good in other domains such as mechanical, electrical, and control. Thus, the possibility of sharing or reusing the model developed by the field expert into different applications and systems may help address the lacking expertise. Besides, various domain-specific modeling and simulation tools solve their problem effectively [5]. Therefore, it will also be beneficial to let those tools solve that particular system or subsystem model. The results can be communicable through the standard interface to other subsystem models. Further, to keep the quality and integrity of the simulation results, it is necessary to evaluate models in terms of accuracy and standardization.

Co-simulation is a process of simulating two or more sub-simulators modules (slaves) generated from the same or different tools. These modules solve individually and exchange the simulated data at a specific interval defined by a master simulation program [5]–[7]. These modular sub-simulators need to follow a standard interface for communication with the master and other slaves. High-level architecture (HLA) and FMI are two basic interface standards for the co-simulation [8], [9]. FMI, a tool independent standard interface, is initiated by the automotive industry and is currently gaining increased attention from other industries. The FMI standard sub-simulators, FMUs, are treated as a black-box, thereby keeping the intellectual property intact [10]. The FMU variables at the communication interfaces and their simulated results are only exposed to the connected sub-simulator or the master simulator.

As FMI is widely adopted in different industrial domains, various commercial and open-source modeling and simulation tools have started implementing FMI to simulate an externally created FMU or export an FMU [6]. The maritime industry is adopting FMI-standard by establishing an open-source ecosystem, called open simulation platform (OSP) [7], to enhance the co-simulation possibilities. The OSP is developed as a joint industry project (JIP) by the maritime industries (DNV GL, Kongsberg Maritime, and SINTEF) with the Norwegian University of Science and Technology (NTNU) as an academic partner. The OSP aims to efficiently develop and maintain the maritime digital twins, enabling system integration, testing, and verification [7]. OSP is not only focusing on the common standards but also increasing the model reuse through industrial collaborations. Besides, OSP has also developed a Co-Sim App (web browser-based co-simulation tool) and graphical system configuration tool ‘Kopl.’ In Kopl, FMUs are graphically interconnected to model a system. The modeled system is then validated and simulated in the FMI-based platform [7].

The co-simulation approach can be used to optimize the system model development process for the ship power and propulsion systems. It enables the parallel development of several subsystems, reducing the time-to-market for the large and advanced simulators. This approach is also being studied, tested, and verified in the maritime industry. Shipboard electric power system modeling based on co-simulation in the OSP platform extends the possibility for hardware- and software-in-the-loop testing and the development of digital twin [7], [11], [12]. The co-simulation can also be an effective tool where the hardware and software can be interfaced for a hybrid testing approach. The multi-level electricity grid with photovoltaic systems [13] and the distributed engine control system [9] are effectively simulated using a co-simulation framework. The virtual prototyping of marine systems using co-simulation is studied in [8], [14], [15]. Moreover, the possibility to select different time step and solver for each FMUs according to the subsystem dynamics increases the computational efficiency while simulating a complex system [16].

The benefits of the co-simulation approach can be demonstrated during the design, development, and operational phase of any system. The shorter simulator development time enables virtual testing. Besides, real-time virtual testing provides a realistic testing bench and the possibility for different testing methodologies. Moreover, the library of the sub-simulators or FMUs with different model accuracy and complexity allows the system integrator to select the FMU with the desired level of model fidelity to achieve the simulation objectives.

The co-simulation approach in the automobile and aircraft industries are quite matured compared to the maritime industry. Some co-simulation cases in maritime industries have been previously explored. However, practical applications of co-simulation in the ship hybrid power system, such as real-time virtual testing or model fidelity testing, are yet to be developed. In this work, the co-simulation of a marine hybrid power system is established based on the FMU and FMI. Most of the FMUs in this study are generated from the system model presented in an earlier paper of the same authors [17]. However, FMUs from other partners and vendors can also be integrated if they comply with the defined interface variables. The simulation cases for the real-time virtual testing and model interchangeability for various levels of model fidelity are simulated.

II. SYSTEM OVERVIEW

The studied ship hybrid power system is illustrated in Fig. 1. A diesel generator set and a battery bank are energizing each side of the power buses connected through a bus-tie breaker. The propulsion loads are driven by the induction motors connected on both sides of the buses. Both low- and high-level control systems used to achieve the control objectives in the generation- and propulsion-side of a hybrid power system are modeled. Some of the power converters are modeled using the ideal semiconductor switch models, whereas others are average models. The rated parameters for different components are presented in Table I.

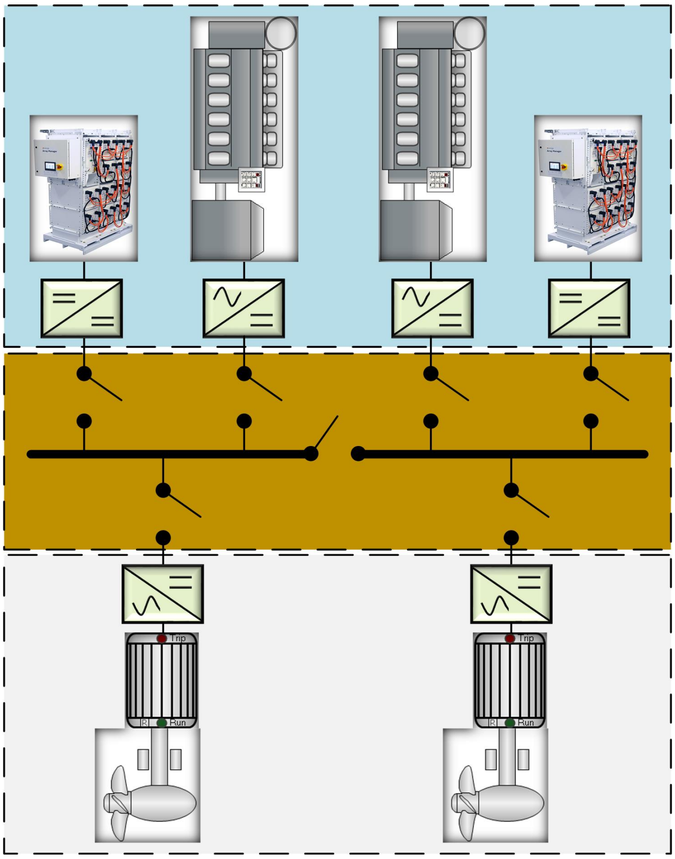


Fig. 1: Battery-based ship hybrid power system.

TABLE I: Rated component capacities of the studied system.

Components	Capacity	
	Bus 1 (left)	Bus 2 (right)
Diesel engine	380 kW	225 kW
Generator	360 kW	207kW
Rectifier	378 kW	218kW
Battery	22.5 kWh	22.5 kWh
DC-DC Converter	70 kW	70 kW
Inverter	168 kW	168 kW
Motor	160 kW	160 kW

III. METHODOLOGY

For the simulation of a marine hybrid power system in a co-simulation framework, the modular sub-simulators in the form of FMUs have to be developed. The previously developed bond graph-based DC-hybrid power system [17] is taken as the basis for this work. The system model is divided into subsystems based on the component and subsystem supplier in the real world. For example, the diesel engine, generator set, rectifier, and necessary control systems for the diesel generator are usually supplied by a vendor; therefore, it is divided as

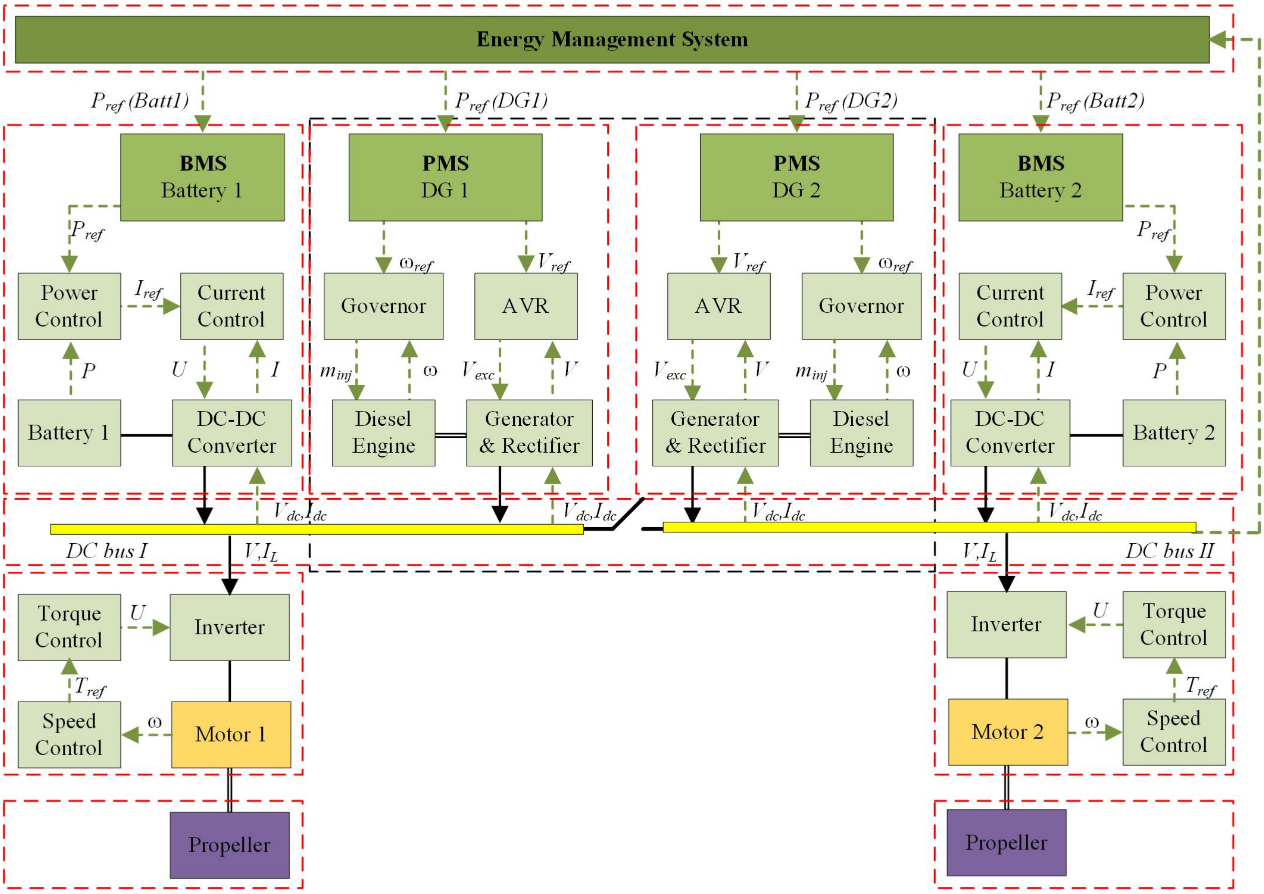


Fig. 2: Division of a system model into subsystems for exporting as FMUs.

a subsystem or an FMU for the co-simulation framework. Other subsystems are also selected using a similar approach. The component models (both physical and control system) are grouped to create the subsystems or FMUs as shown by dashed-red lines in Fig. 2. Each subsystem from the system model is then generated as an FMU using the export function in 20-Sim simulation software [18]. The subsystems or the FMUs have the defined input and output variables as power bonds or signal connections. These input/output variables are analogous to the real system's physical connections and control and measurement signals.

The generated FMUs and other necessary FMUs from external vendors or partners are the slave simulators in the co-simulation framework. These slave simulators communicate with the master simulator via a standard interface, FMI. A master simulator is a simulation tool developed as open-source software, such as Kopl and Co-Sim App developed by open simulation platform or commercial software such as 20-Sim, and Simulink. The generic overview of co-simulation setup is illustrated in Fig. 3.

A. Virtual Testing

To ensure the proper functioning, the safety of humans, material, and the environment, and in line with different stringent regulations, testing several functionalities, components,

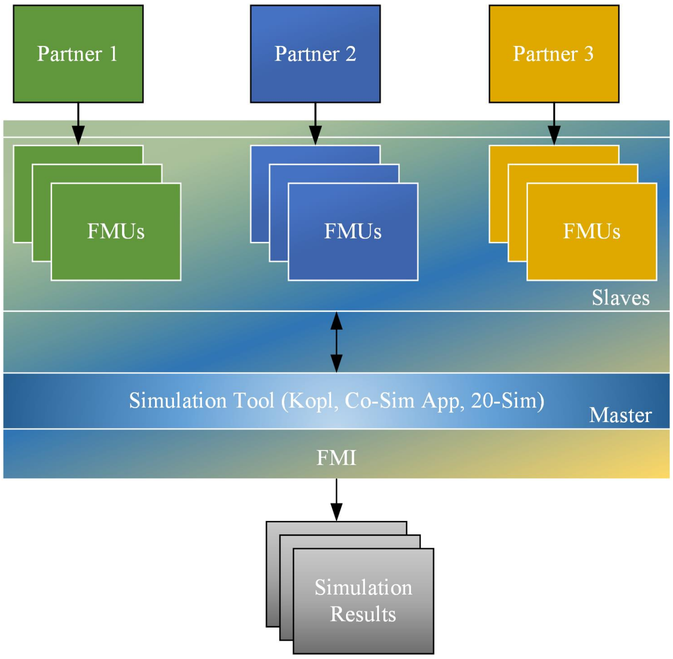


Fig. 3: Generic overview of co-simulation setup.

subsystems, and systems becomes imperative. The use of real physical assets in these testing processes is costly and risky and considerably increases the development time for any system [19]. Moreover, various conditions and scenarios during the design, development, and operation can be created and tested virtually using the simulation tools [20].

B. Model Fidelity

The accuracy of the simulation results depends on the model fidelity. How detailed modeling is done may reflect how accurate results are. Higher the model fidelity, higher will be the model complexity and the computational effort [3]. Model fidelity depends not only on how the models are developed but also on how the models are simulated [21]. Thus, various degrees or levels for the model fidelity can be defined. Depending on the objectives of simulation, the required model fidelity needs to be selected. The co-simulation framework supports the implementation of various model fidelity FMUs if they have the defined interface variables. Therefore, a library of FMUs with various model fidelity levels allows modularity and interchangeability. It enhances the possibility of model selection to achieve various simulation objectives. The development of the library at the FMU level is beneficial over the component level. It helps eliminate the tuning of various parameters with different fidelity models, thereby reducing the system model development time.

IV. RESULTS & DISCUSSIONS

Different simulation cases are developed to present real-time virtual testing and FMU interchangeability based on various levels of model fidelity in FMUs. In general, the propulsion load fluctuates due to environmental variations like wind, waves, and water current. The environment and vessel are not modeled. Therefore, the propeller units are modeled as load power with random noise.

1) Real-time Virtual Testing: The developed co-simulation setup can be used for virtual testing of both the generic operational functioning and manually introduced failure conditions. As a generic scenario, the proportional load-sharing among the energy carriers available in a bus is tested. Further, the battery implementation strategy is improved to damp the power fluctuations and high rate of power change in the generator using a battery. The Bus-tie breaker is left open in both cases, thereby isolating the buses. Both the simulation scenarios can simulate at least two times faster than real-time, opening the possibility for real-time applications and testing frameworks.

If the onboard battery has a high enough capacity to bear the propulsion and auxiliary load, it can share the load with the primary power generators. One way to share the power can be proportional sharing, where the energy carriers share the power according to their nominal capacities. Virtual testing of the proportional load-sharing between the generator and battery is presented in Fig. 4. This method can be more feasible for the vessel with the possibility of onshore battery charging or plug-in hybrid vessels.

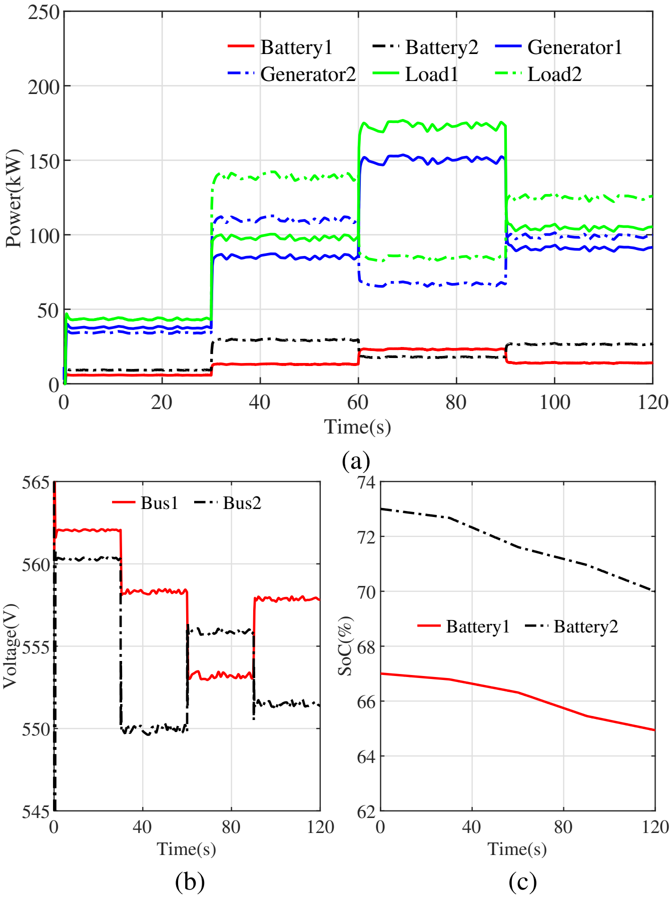
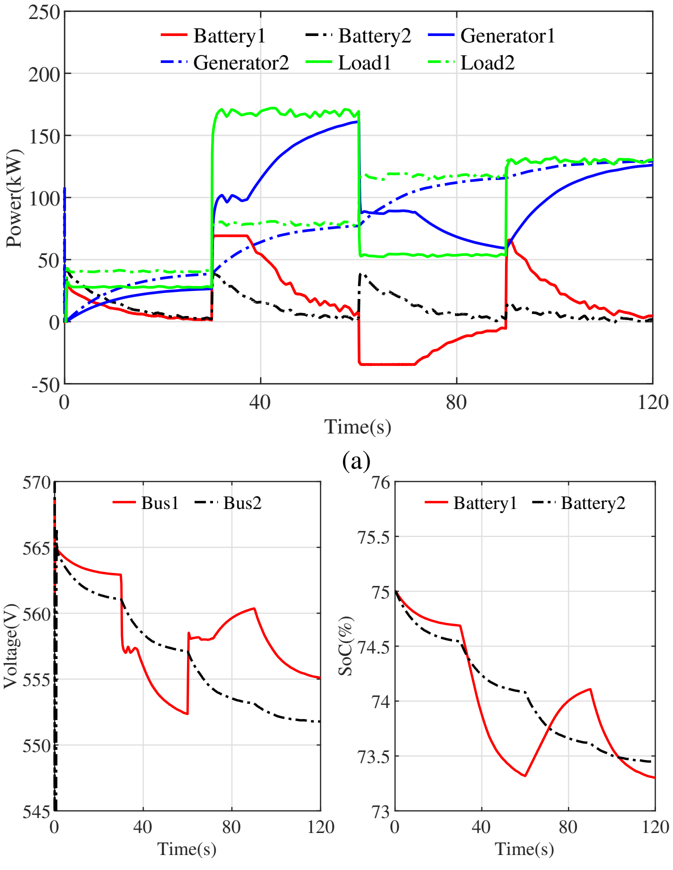


Fig. 4: Virtual testing of proportional load-sharing in a hybrid power system with an open bus-tie breaker. (a) Power. (b) Bus voltage. (c) Battery SoC.

It is not always feasible to install large batteries onboard to proportionally share the power with other power generators due to their weight and volume. In such cases, the battery can be used to enhance the dynamic system performance for the highly dynamic loads, shave the peak loads, or smoothen the generator powers. A battery implementation methodology based on the load dynamics combining the enhanced dynamic performance and power smoothing is virtually tested when the buses are isolated using a co-simulation approach as shown in Fig. 5. This battery implementation strategy helps to cope with high dynamic loads and dampens the generator power fluctuations. This method can have high importance for the vessels with slow dynamic power generators such as gas engines and hydrogen fuel cells.

2) Model Fidelity: The model fidelity test for the advanced EMS is also virtual testing of a control strategy in the hybrid power system. To demonstrate the implementation of the FMUs with different model fidelity, the F1EMS or the FMU representing EMS is replaced with a more advanced EMS strategy implemented in an FMU called F1EMS_V2. It is the modified version of the one presented in [17]. While developing new FMUs with different model fidelity, it should



(a)

(b)

(c)

Fig. 5: Virtual testing of load-based battery implementation method in a hybrid power system. (a) Power. (b) Bus voltage. (c) Battery SoC.

be taken care not to alter the variables at the interface. In the new EMS sub-simulator, a rule-based control is implemented to run the generators in an optimal region such that batteries complement them as shown in Fig. 6.

The buses are isolated until $120s$. The bus-tie breaker is closed at $120s$ resulting in a common bus for further simulation. When it is a common bus, generator 1 is set as the master generator such that it is responsible for maintaining the bus voltage. In normal operating conditions with the bus-tie breaker in a closed position, battery 1 is designed to act as a spinning reserve. However, in case of failure in any other power carriers, it can come into action. Depending on the load power, bus-tie breaker position, and available energy carriers, EMS selects a different combination of energy carriers to supply the load demand and ensure the batteries' sufficient charge level. The load power demand and the power response from the generator and battery are shown in Fig. 6(a). The bus voltage and battery SoC responses are presented in Fig. 6 (b) and Fig. 6(c), respectively.

When the buses are isolated, the load power demand usually is not enough for generators to run in the optimal region. Therefore, the battery is actively used to supply the lower power demand. When the power demand is higher than battery discharging capacity, the generator activates to supply the load and charge the battery with available power. It helps to move the generator power towards the optimal region, saving fuel consumption.

When the bus tie-breaker is closed, the load power demand, in general, is enough to allow the master generator to run in the optimal region. The other generator activates only if the master generator and the active battery cannot optimally supply the load (at interval $180-210s$). Where possible, the battery is smoothing the generator power (at interval $120-150s$ and $210-240s$).

V. CONCLUSION

A co-simulation-based system model with FMU/FMI is developed and tested for a marine hybrid power system. Standard interfaces become beneficial, especially to connect the subsystem models from different vendors and partners while keeping the intellectual property intact. The possibility to assign an individual time step and the type of solver for the FMUs increases the flexibility during simulation, thereby improving the computational efficiency. The FMUs with faster dynamics can have a lower time step for the simulation, while others with relatively higher time steps. Similarly, the various solver can be selected based on the desired stability, accuracy, and computational effort.

Software from OSP is used to develop the system model using FMUs. The developed system models can simulate faster than real-time, signifying their use in real-time applications and testing. The simulation cases for virtual testing and model fidelity are developed. It is observed that the co-simulation approach is efficient while developing the system model for real-time virtual testing. Besides, the interchangeability of various fidelity FMUs enhances modularity. It also increases the efficiency and effectiveness of the simulations based on objectives, accuracy, and computational effort.

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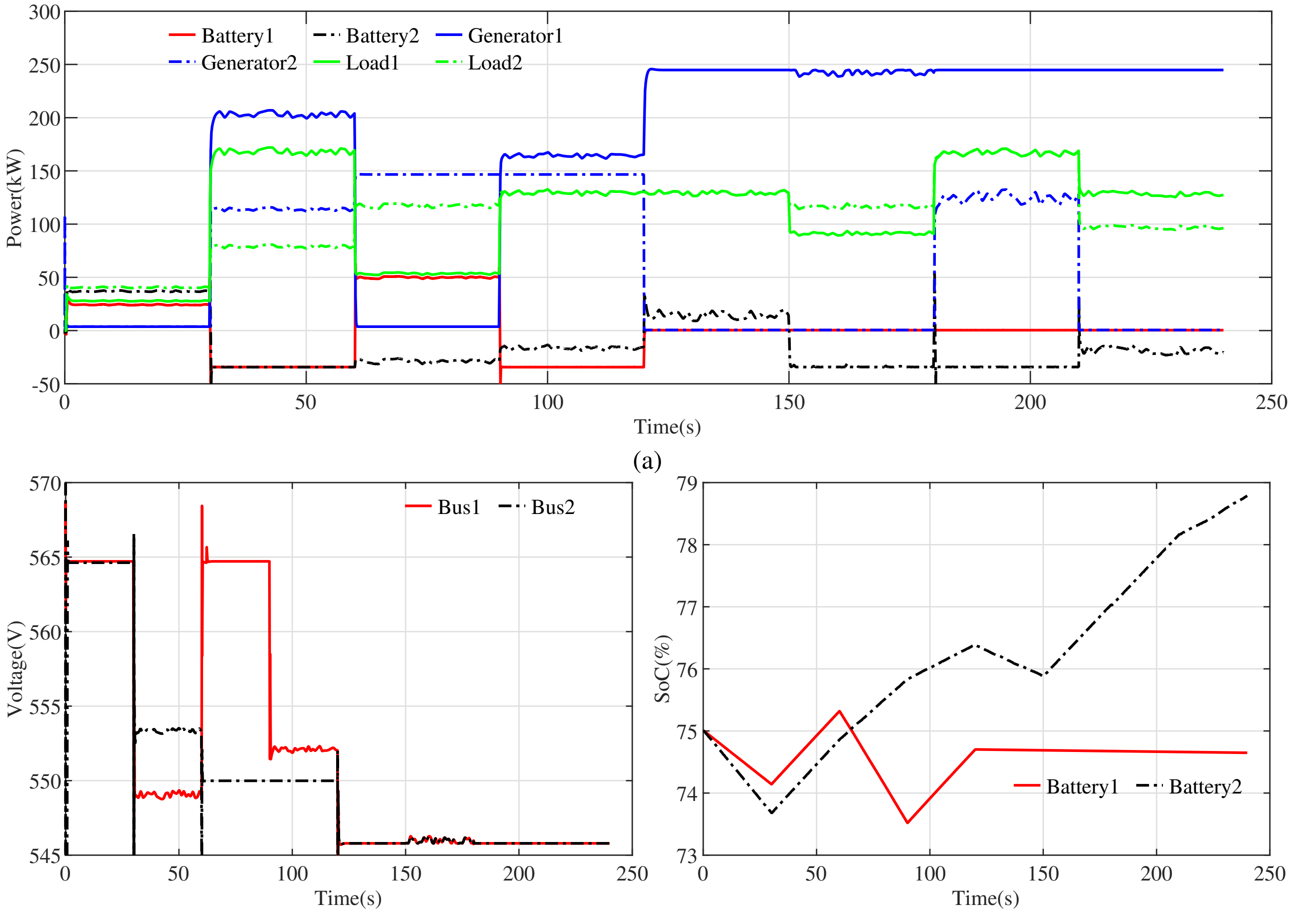

(a)

(b)

(c)

Fig. 6: Model fidelity testing for the EMS in a hybrid power system. (a) Power. (b) Bus voltage. (c) Battery SoC.

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