Digital Twin Modelling of Ship Power and Propulsion Systems: Application of the Open Simulation Platform (OSP)

Florian Perabo
Department of Marine Technology
Norwegian University of Science and Technology
Trondheim, Norway
florian.perabo@ntnu.no

Daeseong Park
Department of Marine Technology
Norwegian University of Science and Technology
Trondheim, Norway
daeseong.park@ntnu.no

Mehdi Karbalaye Zadeh
Department of Marine Technology
Norwegian University of Science and Technology
Trondheim, Norway
mehdi.zadeh@ntnu.no

Øyvind Smogeli
Group Technology and Research
DNV GL
Trondheim, Norway
oyvind.smogeli@dnvgl.com

Levi Jamt
Group Technology and Research
DNV GL
Trondheim, Norway
levi.jamt@dnvgl.com

***Abstract*—Today, modelling and simulation technologies are extensively used in the maritime industry. As a reaction to changing market demands and environmental challenges, maritime systems are becoming more complex and coupled. Digital approaches such as digital twins and co-simulation are coping these challenges and offer new opportunities throughout the lifecycle of a vessel. In this work, we present the digital twin modelling and the co-simulation of a typical AC ship power and propulsion system including the power stage, relevant local controllers and a high-level controller. The power and control components are modelled individually and exported as Functional Mock-up Units (FMUs). To perform a co-simulation of the ship electric power system, the Open Simulation Platform (OSP) is utilized. This co-simulation environment connects the individual FMUs and routes the data between the sub-simulators of the digital twin. A typical test scenario is carried out to demonstrate the correct functioning of the ship power and propulsion system as well as the OSP environment.**

Keywords—Digital Twin Modelling, Co-Simulation, Open Simulation Platform (OSP), Ship Power System, Digital Ship.

I. INTRODUCTION

Today, more than ever, the maritime industry is facing numerous challenges following from new market demands [1], stricter environmental regulations [2] and an accelerating technological evolution. To cope with these challenges, it is inevitable to cut costs and to increase the overall efficiency, reliability, and sustainability of maritime systems. Modern ship electric power and propulsion systems are a crucial factor for reducing costs and the environmental impact of the maritime industry. Though, the integration of power electronic converters is key to enable ship electrification including energy storage systems (ESS) and new energy sources [3]. Together with advancing control systems such as Power and Energy Management Systems (PMS/EMS), these technologies work towards reduced fuel consumption and increased overall performance of the vessel.

At the same time, these trends increase the complexity of a vessel's power and control system. Usually, a vessel's system components are developed independently by different suppliers using specialised software tools making model integration for simulation a difficult task. Due to the high costs of prototypes, and the lack of availability of both hardware and software systems before systems are integrated into the ship, it is common to perform system integration and the main testing late in the shipbuilding process and during sea trials. Digital approaches such as Hardware-In-the-Loop (HIL) and Software-In-the-Loop (SIL) testing, and co-simulation using digital twins, cope with these challenges and enable early and continuous simulation-based testing. In recent years, the digital twin approach has been successfully adopted by the aerospace and automotive industry [1]. Now, also the maritime industry is introducing this concept to make use of its great potential [4].

The concept of a digital twin was first introduced as "Conceptual Ideal for Product Lifecycle Management" by Grieves in 2002 [5]. Within the field of engineering, one can define a digital twin as a dynamic set of digital models that fully describes an actual or a potential physical system or subsystem and accurately represents its behaviour in operation [5]. To distinguish this definition from other applications and types of digital twins, the term "system digital twin" is used in this work. A system digital twin combines all available information at any point in the lifecycle of the underlying system [4] and equals an overarching database of the digital representation [1]. Within this approach, any information on the physical system can be obtained from its digital couple [5].

A system digital twin is not only limited by the implementation of multi-physics models but can also be extended by sensor data from the real ship (physical twin) thus achieving a more predictive model. The resulting insights can be used for system improvements, predictive maintenance or - in the case of a system digital twin that also incorporates the control systems from the real asset - virtual commissioning and integration of the system without needed access to the physical asset. Having established a system digital twin, it can be subsequently used to virtualize the system design, construction and operation throughout the lifecycle of a ship (Fig. 1).

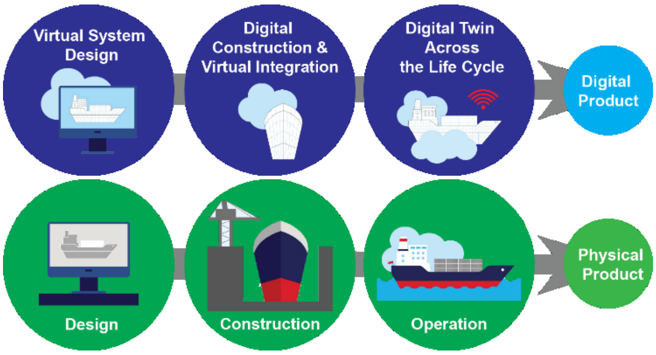

Fig. 1 Using a system digital twin to virtualize the ship systems throughout the lifecycle of a ship.

The modelling of a system digital twin requires a comprehensive understanding of the entire system. For an accurate virtual representation and reliable simulation results, the modelling must be carried out at an appropriate level of detail and fidelity for the underlying purpose [6]. The system digital twin undergoes a continuous optimization process throughout the lifecycle while reaching different levels of maturity and reducing the level of risk. Concurrently, the real data and the simulation results can be analysed and used to verify and improve both the virtual model and the real system.

Since marine systems such as ships are becoming increasingly complex and consist of many subsystems from different engineering domains, traditional simulation approaches are too inflexible, too costly, and too inefficient [6]. Recently, there has been some research showing that co-simulation can be an appropriate simulation approach to overcome these difficulties [6]–[9]. With *Coral*, a co-simulation software built around the Functional Mock-up Interface (FMI) standard has been developed to enable cross-platform integration and simulation of maritime (sub)systems [7]. Extending this concept, the Open Simulation Platform (OSP) has been established to create a collaborative and standardized ecosystem for the maritime industry using the digital twin approach to perform co-simulation and to share models efficiently and securely [10].

In this paper, it is shown how a system digital twin of a typical AC ship power and propulsion system can be modelled and how the OSP can be used for system integration and co-simulation. Based on this, a co-simulation demonstrator is developed, and several simulations are performed to prove the concept of the OSP environment.

II. MODELLING OF SHIP POWER AND PROPULSION SYSTEMS

Fig. 2 shows a typical AC diesel-electric ship power system as it can be found in cruise ships, ferries, icebreakers, drilling ships, cables layers and research ships. Power converters in hybrid-power systems with an AC distribution system are mostly used to connect the propulsion motors and EES such as batteries [3].

The power system consists of two main switchboards, each of which is supplied by a 3-phase salient-pole synchronous generator. The prime movers are diesel-fuelled combustion engines directly coupled with the generator.

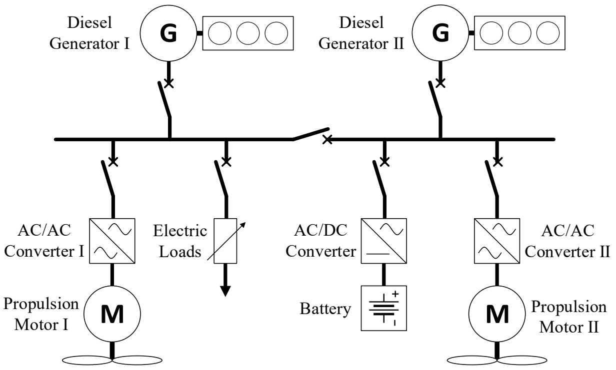

Fig. 2 Single Line Diagram of the Ship Power and Propulsion System

The main power consumers are the two inverter-fed propulsion motors, which are implemented as asynchronous machines. Other large consumers such as pumps or winches are subsumed together with the hotel loads and smaller consumers. Also, a battery storage system is integrated into the power system.

While the local control of the power components is performed by dedicated controllers such as governors and automatic voltage regulators, the high-level control of the power system is done by a Power Management System (PMS).

The individual power components and controllers are modelled and implemented in MATLAB/Simulink. To perform a co-simulation within the OSP environment, the ship power and propulsion system is divided into submodules (see section V) which can be exported as stand-alone FMUs.

A. Diesel Generators

The dynamics of the diesel engine are given by the following transfer function describing the relation between the generated torque $\mathrm{T_m}$ and the fuel index Y [11]:

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

where 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. The generator is modelled as a 3-phase salient pole synchronous machine in the dq-reference frame and the torque balance on the shaft is represented by a swing equation:

$$J_m \dot{n} = T_m - T_e - T_f \quad (2)$$

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

To maintain constant engine speed, a governor controls the engine's fuel supply Y as a function of the difference between measured speed n_{mes} and reference speed n_{ref}. The implemented governor is derived from [11] and acts as a PI controller including an anti-windup in the integration action. The terminal voltage of the generator is controlled by an AVR, setting the excitation voltage V_f based on the difference between the reference voltage V_{ref} and the measured terminal voltage V_m.

B. Switchboards

The ship power system consists of two main switchboards connecting the power components via circuit breakers. The switchboards are implemented as simple connection lines assuming no relevant dynamics. The circuit breakers are modelled as switches which have a high resistance (1e6 Ω) in open condition and a small resistance (0.01 Ω) in closed condition. The breaker switching is controlled by the PMS which also monitors the switching conditions.

C. Electric Propulsion Drives and Control

The electric propulsion of the vessel is provided by two equally modelled asynchronous machines driving a propeller each. The machines are modelled as 3-phase squirrel cage induction machines in the *dq*-reference frame. The motors are fed by AC/AC converters consisting of a six-pulse diode rectifier and a two-level inverter using IGBTs. As a control strategy for the variable frequency drive, direct-torque control with space vector modulation (DTC-SVM) is utilized. For this, the magnetic stator flux $\boldsymbol{\psi_s}$ and the electromagnetic torque T_e of the induction machine are calculated in the dq-reference frame based on the stator current $\boldsymbol{I}_s$ and the stator voltage $\boldsymbol{V}_s$ of the motor:

$$\boldsymbol{\psi}_s = \int (\boldsymbol{V}_s - R_s \boldsymbol{I}_s) dt \tag{3}$$

$$T_e = \frac{3}{2}\frac{p}{2}\left(\psi_{sd} I_{sq} - \psi_{sq} I_{sd}\right) \tag{4}$$

where R_s is the stator resistance and p the number of poles of the machine. The estimated and reference values of the torque and the flux are controlled by PI controllers and an SVM logic generates the pulses driving the IGBTs of the inverter. The control scheme of the DTC-SVM is shown in Fig. 3.

The shaft connecting the motor and the propeller is described by a swing equation. The dynamics of the fixed-pitch propeller are not implemented but substituted by a varying torque T_{prop} which is derived from the actual power P_{prop} needed for propulsion and the shaft speed n_{prop}:

$$T_{prop}(t) = \frac{P_{prop}(t)}{n_{prop}} \tag{5}$$

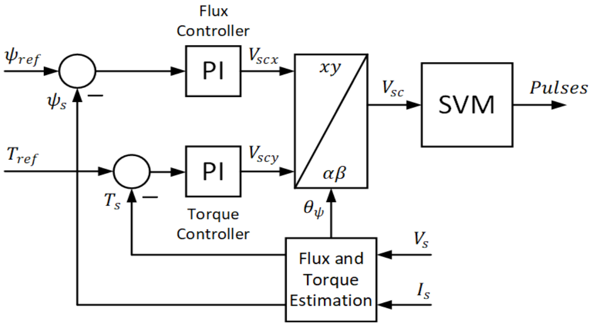

Fig. 3 Control scheme of a Direct Torque Control with Space Vector Modulation (DTC-SVM)

D. Auxiliary and Hotel Loads

The machinery for cargo handling and the hotel loads are modelled as three-phase dynamic loads. The active and reactive power consumption can be independently changed during the simulation thus representing different loading conditions of the power system.

E. Power Management System

The high-level control of the power system is performed by a PMS providing functionalities such as generator synchronisation, droop based active and reactive load sharing and load-dependent start-stop of gensets.

To connect a generator to a live bus bar or to close a bus tie between two live switchboards, both systems must be synchronized. The implemented PMS monitors the relevant voltages and adjusts the reference speed of the governor and the reference voltage of the AVR to synchronize the generator's frequency, phase angle and voltage magnitude with the relevant bus bar. Once the synchronization requirements are met, the breakers are closed, and the power of the generators can be adjusted again.

The PMS includes a reactive and active droop controller for each genset. Reactive power-sharing is realized by adjusting the reference voltage V_{ref} of the generator's excitation system, the AVR. The required excitation voltage is calculated based on a power-sharing factor K_{QV} and the actual reactive power Q_m provided by the generator:

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

where V_0 and Q_0 are the voltage and reactive power at no-load condition respectively. In contrast, active power-sharing is realized by adjusting the reference speed n_{ref} of the governor. Based on a power-sharing factor K_{Pf} and the actual active power P_m provided by the generator, the required reference frequency f_{ref} is calculated by a droop speed controller:

$$f_{ref} = f_0 - K_{Pf}(P_m - P_0) \tag{7}$$

where f_0 and P_0 are the frequency and active power at no-load condition respectively. The governor's reference speed n_{ref} is deviated from the reference frequency f_{ref}.

For load-depending start-stop of gensets, the generated and the consumed power are monitored constantly. If the power difference falls below a specified margin, an additional generator is started, synchronized and connected to the bus bar. If the margin of the available power increases again, the additional generator can be disconnected from the bus bar and stopped to save fuel.

F. Battery

To integrate an ESS in the power system, a Li-ion battery connected by an AC/DC converter can be considered. According to the implemented model, the output voltage is determined based on its state of charge (SOC) and C-rate. Therefore, the current output is controlled by a converter to produce the power set-point defined in the PMS (it can be varied according to the system configuration). Therefore, the measurements from this module should be voltage, current output, and estimated SOC from its battery management system (BMS). Detailed temperature or cell balancing controls are excluded from this study.

III. CO-SIMULATION FOR SHIP POWER SYSTEMS

A. *Co-Simulation*

In co-simulation, the global simulation of a coupled system is performed by orchestrating the independent simulations of different subsystems [12]. Within this approach, the simulators of each subsystem are loosely connected and the data exchange between them is performed at discrete time steps. Each simulator can be considered as a “black box” reflecting the behaviour of its corresponding subsystem and includes a solver with an appropriate step size. A master algorithm provides communication between the simulators and defines the mapping of input and output variables. Co-simulation has the potential to reduce the overall simulation time by using model-specific solvers and time steps and by sharing the computational load among different computers or processor cores [6].

The co-simulation approach facilitates the independent development and exchange of system components by different teams or suppliers. Due to this, it is possible to focus on a specific part of the coupled system without solving the global problem. Furthermore, co-simulation allows each team to make use of their development platform including specialised techniques, tools and solvers (Fig. 4). This increases the development speed and the model accuracy while protecting intellectual property rights (IPRs) of the model implementation in a “black box”. The complexity and fidelity of simulators vary greatly depending on their type and intended use. Simulators are not only limited to numerical models but can also be the interfaces to sensors, human-machine interfaces or industrial control systems.

To enable efficient communication between the different simulators, a standardized simulation platform including a well-defined communication interface is needed. This ensures the compatibility between different simulators and co-simulation platforms. A common standard for co-simulation is the Functional Mock-up Interface (FMI) which was firstly introduced in the automotive industry.

Fig. 4 Co-simulation allows the modelling of complex systems using different software and development platforms.

B. *FMI-Standard*

The Functional Mock-up Interface [13] is a tool independent standard for the exchange of dynamic models and co-simulation. The standard was initiated by the automotive industry to improve the exchange of simulation models between suppliers and OEMs. Today, the FMI standard is supported by numerous tools and heavily used in industrial and academic projects [14].

The FMI standard differentiates between two main parts: *FMI for Model Exchange* and *FMI for Co-Simulation*. FMI for Model exchange is intended for models that are described by differential, algebraic and discrete equations that can be exported to other modelling and simulation environments supporting the standard. The solver is not included in the model and must be provided by the simulation tool. In contrast, the intention of FMI for Co-Simulation, which is used in this work, is to couple two or more models including individual solvers in a co-simulation environment. The models are solved independently from each other, and the data exchange is restricted to discrete communication points. This approach is based on a master/slave paradigm where a master algorithm controls the data exchange and the synchronization between all sub-simulators (slaves). [14]

Defined by the FMI standard, the models can be wrapped as Functional Mock-up Units (FMUs), which are archive files containing all necessary components to utilize an FMU for model exchange or co-simulation. The FMU-archive not only contains the model code for one or more computing platforms but also metadata and documentation. FMI specifies a standardized XML scheme for the metadata defining all variables of the model as well as an interface to connect the model code with external simulation tools [14]. An FMU for co-simulation can be considered as a replacement of a real (sub)system ready to take inputs and to compute a resulting behaviour [12]. This is closely related to the definition of a system digital twin used in this work.

IV. OPEN SIMULATION PLATFORM

A. *Background*

The grand vision of the Open Simulation Platform [10] project is to create a maritime industry ecosystem for co-simulation and managed sharing of “black-box” simulation models, building on the FMI standard for co-simulation. This will facilitate the effective building of system digital twins and vessels, which in turn can be used to solve challenges with designing, building, integrating, commissioning and operating complex, integrated systems. The OSP Joint Industry Project (JIP) was founded by DNV GL, Kongsberg Maritime, Norwegian University of Science and Technology (NTNU), and SINTEF in 2018, who subsequently have been joined by 20 industry partners [10]. The JIP will produce a set of open-source deliverables to enable the industry and academia to work in a more standardized way with co-simulation. This will help build interoperability between models and platforms and aid the industry when going forward with collaborative simulations and future ship designs. The OSP open-source software will be made available on GitHub in June 2020 [15].

B. *Architecture*

The open-source software coined the Core Simulation Environment (CSE) produced in the OSP JIP consists of the following elements: C/C++ co-simulation library, Demo application, Command-line interface, Model interface validator and CSE Java wrapper.

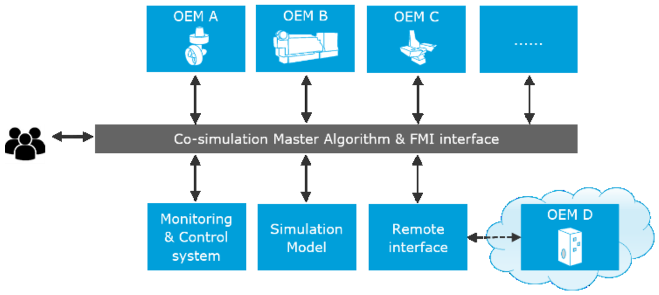

Fig. 5 Conceptual architecture of the Open Simulation Platform

The C/C++ co-simulation library handles the co-simulation of FMU models configured as system structures with the System Structure & Parameterization (SSP) standard [16] or the new model interface standard Marine System Model Interface (MSMI) developed in the OSP project. CSE includes a fixed-step master algorithm, scenario runner, and features to observe and manipulate simulation variables.

The demo application is developed to showcase how the CSE co-simulation library can be used in an application and to provide a simple graphical user interface for easy exploration of the library's features. With the command-line interface, the co-simulation library is used to enable co-simulation from the command-line. The Model interface validator is a tool to verify that the simulation model complies to MSMI. Lastly, the Java wrapper enables Java applications to make use of the co-simulation library.

The conceptual architecture of the OSP is shown in Fig. 5. The FMUs are connected to the standardized FMI co-simulation interface provided by the CSE. Based on the input-output parameter mapping included in a dedicated interface specification file, the OSP master algorithm routes the data between the FMUs. A scenario management tool allows change of the system parameters automatically based on a scenario file. Input and output parameters of all FMUs can be logged in dedicated data files based on predefined rules.

Using the OSP Core Simulation Environment to orchestrate the co-simulation, FMU models can easily be added and interconnected. Currently, the OSP is supporting FMI 2.0 and FMI 1.0 and will be updated to support FMI 3.0 when this standard becomes operational.

V. APPLICATION OF THE OPEN SIMULATION PLATFORM

A. *System Boundaries & Model Integration*

When it comes to co-simulation of a complex system such as the implemented ship power and propulsion system, one of the main challenges is to define appropriate system boundaries between the different subsystems. Based on these subsystems, the full-system simulation is decoupled into individual sub-simulators which can be also called system digital twin components.

How to divide the total system into different parts depends on the purpose of the co-simulation. Higher modularity increases the interchangeability and makes it possible to include models with different fidelity. On the other hand, higher modularity increases the system complexity and causes a higher need for communication between the sub-simulators. Therefore, it is important to find a good balance between modularity, complexity, accuracy and numerical stability when defining the system boundaries [6]. In practice, the system boundaries will be mainly defined by the suppliers providing the "black box" models of the different subsystems.

The system boundaries of the ship power and propulsion system represented in this work are drawn according to the fidelity and accuracy needs for this study, as well as the different engineering domains of the subsystems. The full-system simulation is split into four kinds of sub-simulators: Diesel engines, electrical power system, propellers and PMS. The mechanical systems, namely the Diesel generators and propellers, can be less accurate while the electrical power system needs a higher model fidelity. Due to this, all of the electric power components are included in a single FMU.

To export the subsystems as FMUs, they are implemented independently as separate MATLAB/Simulink models. Each model contains an interface with the input and output parameters of the subsystem. The step size of each FMU can be chosen individually as a fixed multiple of the base step size. A smaller step size results in a more accurate simulation but also increases the computation time needed to solve the simulation. The solver selection should be based on its robustness, computational speed and solution stability as well as the system dynamics.

The models are exported as stand-alone FMUs, adhering to the FMI 2.0 standard, by utilizing an external MATLAB toolbox. Table I summarizes the FMUs used in the co-simulation setup, including their local time-discrete solvers and corresponding step sizes. The base step size was set to $50e^{-6}\ s$. Besides the FMUs and the CSE, the co-simulation setup also includes a dedicated file to define the connections between the FMUs and a scenario definition file. All results are logged in dedicated data files based on predefined rules.

TABLE I. FUNCTIONAL MOCK-UP UNITS AND SOLVERS

Functional Mock-up Unit	**Solver**	**Step Size [s]**
Diesel Engine I & II	Runge-Kutta, 4th order	50e-6
Electric Power Plant	Euler, 1st order	50e-6
Propeller I & II	Euler, 1st order	0.1
Power Management System	Euler, 1st order	100e-6

B. *Test Scenario*

To verify the correct functioning of the Open Simulation Platform on a system level, a simplified power system model is used. The focus of the test scenario is on the high-level control of the power system and the load dispatch between the gensets. Due to this, the dynamics of the power converters and other active components are not considered in the model. In contrast to section II, the propulsion drives and other loads have been replaced by dynamic loads and the ESS has been neglected. The model parameters are given in Table II.

TABLE II. 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

To study the system dynamics and the behaviour of the controllers, the system is simulated for 80 s using the stand-alone FMUs (Table I) and the OSP CSE. The simulation events are summarized in Table III and Fig. 6 shows the response of the power system. A load increase results in a voltage drop and the frequency is decreased by the frequency droop controller. A load decrease causes the opposite behaviour. Connecting genset 2 to the live bus after synchronization results in an oscillating load distribution between the gensets until the droop controllers regulate the engine speed to obtain an even load-dispatch. The voltage and frequency variations in the steady-state and transient state are within the limits defined by DNV GL [17]. The simulation time is approximately 8 min and depends mainly on the model complexity, the chosen solver and the step size of the FMUs. To validate the results, the same simulation was performed within MATLAB/Simulink. Choosing a 1st order Euler solver and a step size of 50e-6 s, the simulation results are almost identical while the simulation speed is slightly slower.

TABLE III. Simulation Events

Time	Event
20 s	Engines started, genset 1 connected to the bus
22 s	Loads connected and 2 MW requested
30-39 s	Genset 2: synchronization and connection to the bus
39-71 s	Load-sharing genset 1 & 2, several loads requested
71 s	Genset 1 tripped, load take-over genset 2

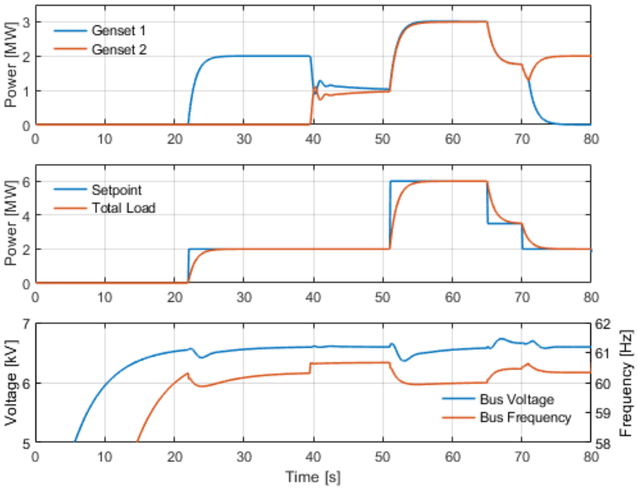

Fig. 6 Load dispatch, total load and voltage quality during start-up, synchronization and parallel operation of two gensets

VI. Conclusion

This paper has presented the digital twin modelling of an electric ship power and propulsion system including the power stage and relevant controllers. It has been shown that digital approaches such as digital twins and co-simulation can be beneficial for the maritime industry thus reducing costs and time. Also, the use of the Open Simulation Platform as a standardized and collaborative environment for co-simulation and model exchange in the maritime industry has been demonstrated.

The developed power system model has been decomposed into stand-alone FMUs and the OSP has been used to reconnect these sub-simulators enabling a full-system co-simulation. The test scenario is used as “proof of concept” and focuses on the validation of the correct functioning of the OSP environment and the modelled power system. It has been shown that the presented co-simulation environment is suitable to analyse the system stability and dynamics within a reasonable time. Additional components such as power electronic devices, gensets, switchboards, loads and controllers can be easily implemented into the power system model. Also, FMUs from different engineering domains such as hydrodynamics (hull, waves) or mechanics (cranes) can be connected within the OSP environment enabling a full-system simulation of a ship.

Acknowledgement

This work has been supported by Korea Shipbuilding & Offshore Engineering Co., Ltd. (KSOE).

References

[1] J. Van Os, ‘The Digital Twin throughout the Lifecycle’, in *SNAME Maritime Convention*, Nov. 2018.

[2] International Maritime Organization, *Marpol ANNEX VI and NTC 2008, 2013: With Guidelines for Implementation*, 2013 ed edition. London: Intl Maritime Organization, 2013.

[3] P. Ghimire, D. Park, M. K. Zadeh, J. Thorstensen, and E. Pedersen, ‘Shipboard Electric Power Conversion: System Architecture, Applications, Control, and Challenges [Technology Leaders]’, *IEEE Electrific. Mag.*, vol. 7, no. 4, pp. 6–20, Dec. 2019.

[4] DNV GL, ‘Digital Twins at Work in Maritime and Energy’, 2017. https://www.dnvgl.com/Images/DNV GL Feature %2303 ORIG2b_tcm8-85106.pdf (accessed Jan. 08, 2020).

[5] M. Grieves, *Origins of the Digital Twin Concept*. 2016.

[6] S. Sadjina, L. T. Kyllingstad, M. Rindarøy, S. Skjong, V. Æsøy, and E. Pedersen, ‘Distributed Co-simulation of Maritime Systems and Operations’, *J. Offshore Mech. Arct. Eng*, vol. 141, no. 1, Feb. 2019.

[7] S. Skjong, M. Rindarøy, L. T. Kyllingstad, V. Æsøy, and E. Pedersen, ‘Virtual prototyping of maritime systems and operations: applications of distributed co-simulations’, *J Mar Sci Technol*, vol. 23, no. 4, pp. 835–853, Dec. 2018.

[8] N. Pedersen, J. Madsen, and M. Vejlgaard-Laursen, ‘Co-Simulation of Distributed Engine Control System and Network Model using FMI & SCNSL’, *IFAC-PapersOnLine*, vol. 48, no. 16, pp. 261–266, Jan. 2015.

[9] Y. Chu, L. I. Hatledal, H. Zhang, V. Æsøy, and S. Ehlers, ‘Virtual prototyping for maritime crane design and operations’, *J Mar Sci Technol*, vol. 23, no. 4, pp. 754–766, Dec. 2018.

[10] ‘Open Simulation Platform - Joint Industry Project for the maritime industry’, *Open Simulation Platform*. https://opensimulationplatform.com/ (accessed Feb. 16, 2020).

[11] R. Izadi-Zamanabadi and M. Blanke, ‘A ship propulsion system as a benchmark for fault-tolerant control’, *Control Engineering Practice*, vol. 7, no. 2, pp. 227–239, Feb. 1999.

[12] C. Gomes, C. Thule, D. Broman, P. G. Larsen, and H. Vangheluwe, ‘Co-simulation: State of the art’, Feb. 2017.

[13] ‘Functional Mock-up Interface’. https://fmi-standard.org/ (accessed Jan. 14, 2020).

[14] T. Blochwitz *et al.*, ‘Functional Mockup Interface 2.0: The Standard for Tool independent Exchange of Simulation Models’, presented at the 9th International MODELICA Conference, Munich, Germany, Nov. 2012, pp. 173–184.

[15] ‘CSE’, *Core Simulation Environment*. https://open-simulation-platform.github.io/ (accessed Feb. 16, 2020).

[16] ‘System Structure and Parametrization’. https://ssp-standard.org/ (accessed Feb. 14, 2020).

[17] DNV GL, ‘Rules for Classification: Ships - Part 4 Systems and components, Chapter 8 Electrical installations’, 2019.