State-of-the-art Full-Scale Simulator for a Ship Hybrid Power System in a Shuttle Tanker

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Synopsis

To maximize efficiency and minimize emissions, ship power systems are transforming from a conventional to more sophisticated power systems, such as battery hybrid-, fuel cell hybrid-, onboard DC-, and fully battery electric power systems. Such sophisticated power systems also raise the complexity due to different power system configurations and utilization philosophies. On the other hand, a realistic simulator system enhances the research and development, engineering, and training of such complex systems. Firstly, simulator can be used to simulate the what-if scenarios onboard a vessel. The ship operators can simulate a scenario which they are encountering or going to encounter soon. From the simulator results, they can observe, understand, and analyze the outcome of such scenario. It helps them make an informed decision for safe and efficient operation. Secondly, the full-scale simulators including the control system can also be used in virtual prototyping of the ship system. During the ship design phase, simulator can be used to evaluate the choice of right producers to meet power system requirements in both intact and worst-case failure (WCF) conditions. Further, power and energy management system (PEMS) needs to ensure effective use of energy carriers (engine generator sets and battery systems) and energy consumers (propulsion system and heavy loads) for the safe, stable, and efficient operation. This work develops and demonstrates a full-scale simulator for a battery-based hybrid power system in a shuttle tanker. The simulator is developed integrating the dynamic component models and control system models. The dynamic component models are developed based on the first principles with varying fidelity. Majority of the required models are previously developed and are available in the in-house model library. However, in this work, physics-based battery systems, DC grid, grid converters and their control counterparts such as battery management-, energy management systems are newly developed. The simulator is used to study the impact of battery in sudden load change and fluctuating loading conditions, where battery systems proved to effectively manage the situations and stabilize the generator output power. Further, the third simulation scenario also showed that the control system ensures sufficient propulsion power even if the worst-case failure occurs.

Keywords: Battery Hybrid Power System; Onboard DC and AC Power System; Power and Energy Management System; Worst Case Single Failure

1 Introduction

Although maritime industry is a backbone of global trade and economy, it is also responsible for significant global emissions, accounting for almost 3% of global greenhouse gas (GHG) emissions (Ghimire, 2022). To reduce or limit emission footprints, collective efforts towards implementing sustainable solutions in each step can be an effective way (IMO, 2021). Both academic institutions and the industries are working hand-on-hand to innovate cleaner, efficient and effective solutions, which can be grouped into greener fuels, and greener technologies

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Authors' Biographies

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(Ghimire, 2022). In a conventional ship power system, generator sets are driven by engines running on fossil fuels, which have been the primary energy source till date. However, due to stricter emissions and efficiency regulations, alternative energy sources are being explored. The green and renewable energy sources include hydro power, wind, and solar energy. The energy produced by the alternative energy sources can be stored in energy storage systems (ESSs) like batteries, super-capacitors, and flywheels, or used to artificially produce greener fuels such as bio fuels or synthetic fuels (e-fuels).

Various greener fuels (green hydrogen, methanol, and ammonia) are being studied and discussed in the maritime industry (ABS, 2020). The challenges of these new greener fuels lie in the economic feasibility, supply infrastructure, and onboard space requirement. Similarly, greener technologies, such as battery-electric, fuel cell-electric, solar and wind energy-based, and hybrid concepts, are also being explored for the implementation in both new ship builds and retrofitting of the existing ships (ABS, 2020; Arief and Fathalah, 2022; Shakeri et al., 2020). These technologies are well-accepted; however, they have some limitations. For instance, these technologies may fit only for a particular ship type or a mission. However, battery-hybrid technology is one of the technically and economically feasible options for the majority of ship types (Ghimire et al., 2024).

Rapid advancement in battery technologies, especially improved energy and power density and reduced cost of lithium-ion battery, is enabling the implementation of hybrid and pure battery-based power system in various industries such as automobile, maritime, offshore, and so on (Othman et al., 2019). Further, lithium-ion batteries outperform the conventional ones because of higher specific energy, open circuit voltage, charging and discharging rate, and cycle life; lower self-discharging rate; and relatively flat discharge curve (Ghimire et al., 2019). The battery hybrid power system in a ship is characterized by the integration of battery system(s) into the conventional ship power systems Ghimire et al. (2019). Battery systems operate in DC power system architecture and can serve both as a power producer and a consumer. For instance, battery can be charged to store the surplus energy when load power suddenly drops, whereas it can be discharged to supply the energy deficit when load power suddenly increases. In other words, battery systems help in stabilizing the onboard power system. It can be also used to charge or discharge in such a way that the fuel consumption of the fossil-fueled engine reduces, and the overall efficiency improves (Miyazaki et al., 2016).

Although integrating the battery or energy storage systems onboard a ship has the potential to improve power system stability, reduce emissions and fuel consumption, it also increases the complexity of overall power system with respect to architecture, control, operation, and maintenance philosophies. For instance, battery systems require the operation within the defined parameters like charging and discharging rate, current, voltage, and temperature to acquire better performance and safety (ABS, 2017). Besides, it also requires sophisticated monitoring and protection systems to enhance both battery life and safety (Ghimire et al., 2019, 2022).

As the ship systems are getting more complex, interactions between the subsystems also increases. Therefore, it is necessary to study and analyze the interactions of these subsystems not only during the operation but also in the research, design, engineering, and development phases. Similarly, to operate and maintain newly integrated components and technologies onboard a ship, requires the proper training of the crew such that they become familiar about the new components and technologies. A realistic simulator system can be a promising solution to the discussed problems (Skjong et al., 2018; Ghimire et al., 2021a,b). The simulation of ship systems in a real ship scenario incorporating the interactions between subsystems serves as an effective tool that can be used during the research, design, engineering, development, operation, training, and maintenance phases (Skjong et al., 2018). However, in some scenarios when a system of interest is defined as a particular system or subsystem, it may not require simulating a whole complex system. Therefore, the simulated needs to be modular enhancing the use of flexible interconnections between different subsystems.

With a full-scale simulator (see Fig. 1), ship owners and operators can benefit from the ship design to operation and maintenance phases. The full-scale simulators including a control system can be used in virtual prototyping of the ship systems. For instance, during the ship design phase, simulator can be used to evaluate the choice of right producers to meet power system requirements in both intact and worst-case failure (WCF) conditions. This helps in effective ship designing and reducing the CAPEX. Similarly, simulator can also be used to simulate the what-if scenarios onboard a vessel. The ship operators can simulate scenarios which they are encountering or going to encounter soon. From the simulator results, they can observe, understand, and analyze the outcome of their actions in such scenarios. It helps them make the informed decisions for ensuring safe and efficient operations.

In the recent decades, as the computational capacity has significantly improved, data-based methods and tools, such as artificial intelligence and machine learning, are increasingly implemented to solve the problems in an effective manner. These methods and tools require sufficient data to train their algorithms in all possible scenarios, which may not always be possible to collect at once in the real world. Therefore, a realistic simulator can also serve as a synthetic data generator to train the algorithms of the modern problem-solving tools.

This work develops and demonstrates a modular full-scale simulator for a battery-based hybrid power system in a shuttle tanker. The simulator is developed integrating the dynamic component and control system models.

Figure 1: A full-scale shuttle tanker simulator. (Source: K-Sim® Navigation simulator.)

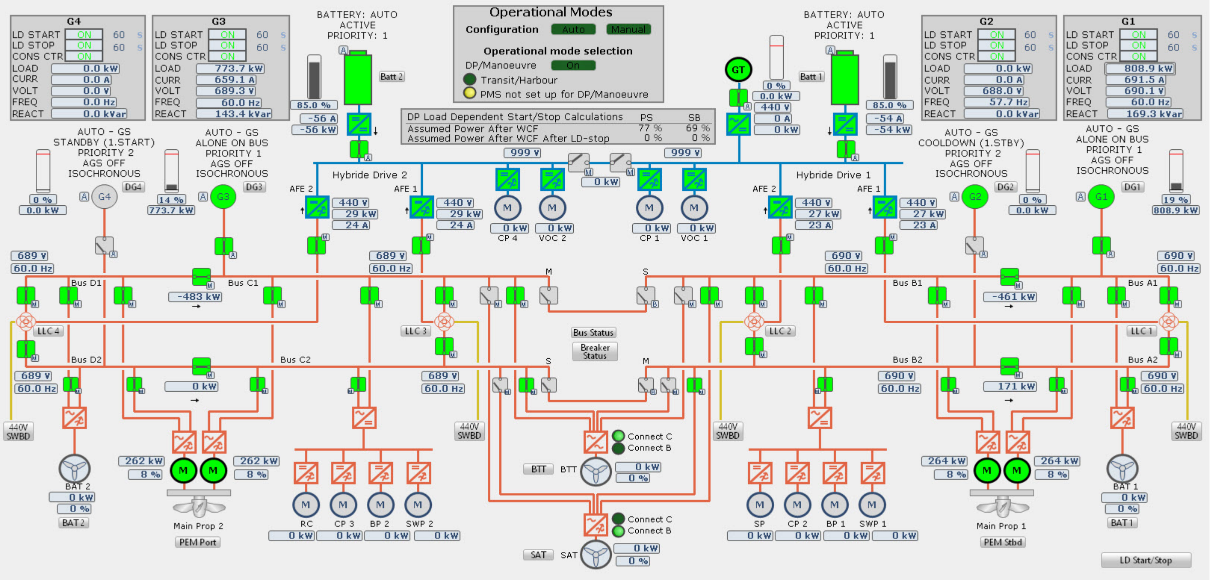
The dynamic component models are developed based on the first principles with varying fidelity. Majority of the required models were previously developed and available in the in-house model library in maritime simulation, Kongsberg Digital (Kongsberg Digital, 2023). However, in this work, physics-based battery systems, DC grid, grid converters, and their control counterparts such as battery management-, energy management systems are newly developed. Simulation scenarios are developed to study the impact of battery systems under sudden load change and fluctuating loads. Another scenario included the testing of worst-case failure-based load dependent start of the generator engines. The simulation results show that the battery systems effectively stabilize the generator engines. Similarly, another scenario simulation shows that the power system redundancy ensures the required power for the propulsion system to maintain the ship position irrespective of the worst-case failure, thus enhancing the safety.

2 A Shuttle Tanker Simulator

A full-scale simulator for a shuttle tanker consists of a K-Sim® Engine and a K-Sim® Navigation simulators. This simulator is interfaced with a real Kongsberg DP software (Kongsberg Digital, 2023). The modeled ship is propelled by two main propellers with a maximum speed of 83.1 rpm each, which are driven by two propulsion electric motors (PEMs) with a power capacity of 3.25 MW each. The propulsion power is also produced by a bow tunnel thruster, two bow azimuth thruster, and a stern azimuth thruster, each of 2.2 MW capacity. The schematic of the simulated power and propulsion system is shown in the Fig. 2.

The power system consists of both AC and DC main switch boards (MSBs), interfaced using four grid converters. The AC MSB is divided into eight different buses using bus-tie breakers, out of which four main buses (Bus A, B, C, and D) are fed through a generator (4.2 MW or 5.6 MW) driven by a dual fuel (DF) engine, operating on marine diesel oil or liquefied nitrogen gas (LNG). These four main buses are divided into two sections (1 and 2) using transformers. AC main buses are operating at 690 V, 60 Hz and are feeding the propulsion loads. Other auxiliary consumers are fed via 440 V power distribution system. The DC main bus is also divided into two by the bus-tie breakers, and named hybrid drive 1 and 2. Both hybrid drives are connected with a battery system of maximum 909 kWh each. Hybrid drive 1 is also connected with a gas turbine of 1 MW capacity. The basic capacities and specifications of the major components of power and propulsion systems are listed in Table A.

Depending on the DP class, the vessel needs to have certain level of redundancy such that in case of a single failure, the redundant system ensures generation of the required propulsion power. With the optimum level of redundancy, this ship model is able to maintain its position and heading even if failure condition occurs. One azimuth thruster and a propeller with two PEMs that can be supplied by two DF generators and a battery system is placed at each side of the engine room. In addition, an azimuth and a bow tunnel can get the power supply from



G4
LD START ON 60 s
LD STOP ON 60 s
CONS CTR ON
LOAD 0.0 kW
CURR 0.0 A
VOLT 0.0 V
FREQ 0.0 Hz
REACT 0.0 kVar

G3
LD START ON 60 s
LD STOP ON 60 s
CONS CTR ON
LOAD 773.7 kW
CURR 659.1 A
VOLT 689.3 V
FREQ 60.0 Hz
REACT 143.4 kVar

G2
LD START ON 60 s
LD STOP ON 60 s
CONS CTR ON
LOAD 0.0 kW
CURR 0.0 A
VOLT 688.0 V
FREQ 57.7 Hz
REACT 0.0 kVar

G1
LD START ON 60 s
LD STOP ON 60 s
CONS CTR ON
LOAD 808.9 kW
CURR 691.5 A
VOLT 690.1 V
FREQ 60.0 Hz
REACT 169.3 kVar

Operational Modes
Configuration Auto Manual
Operational mode selection
DP/Manoeuvre On
Transit/Harbour
PMS not set up for DP/Manoeuvre

DP Load Dependent Start/Stop Calculations	PS	SB
Assumed Power After WCF	77 %	69 %
Assumed Power After WCF After LD-stop	0 %	0 %

Figure 2: Power system overview of a modeled shuttle tanker.

both sides of the main buses.

This K-Sim® Engine simulator for the shuttle tanker is developed integrating various models; dynamic component and control system models. The simulator basically simulates two different categories present onboard a system, namely the physical components available in the engine room and control and automation systems available in the engine control room. The physics-based modeling approach is implemented while modeling the physical components such as DF engine generator set, battery systems, switch boards, breakers, pumps, valves, fluid-based pipe and node models, and so on. Similarly, simulation of control and automation system basically consists alarm system and enables manual, semi-automatic, or automatic operation of a certain component or a system. Most of the models used to develop this simulator were already available in the in-house model library. However, based on the author's previous work (Ghimire et al., 2021a,b,c; Ghimire, 2022), new models for the battery systems are developed in this work including battery management system (BMS), energy management system (EMS), DC-DC converters, DC main bus, and grid converters as shown in Fig. 3.

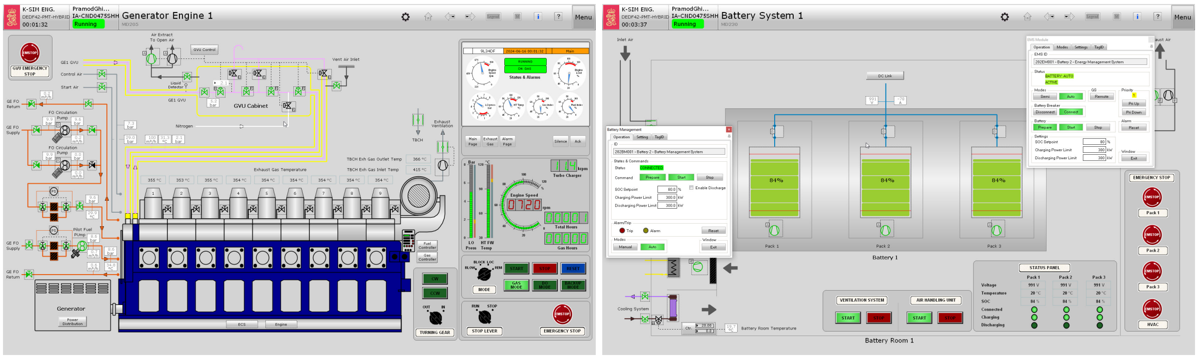


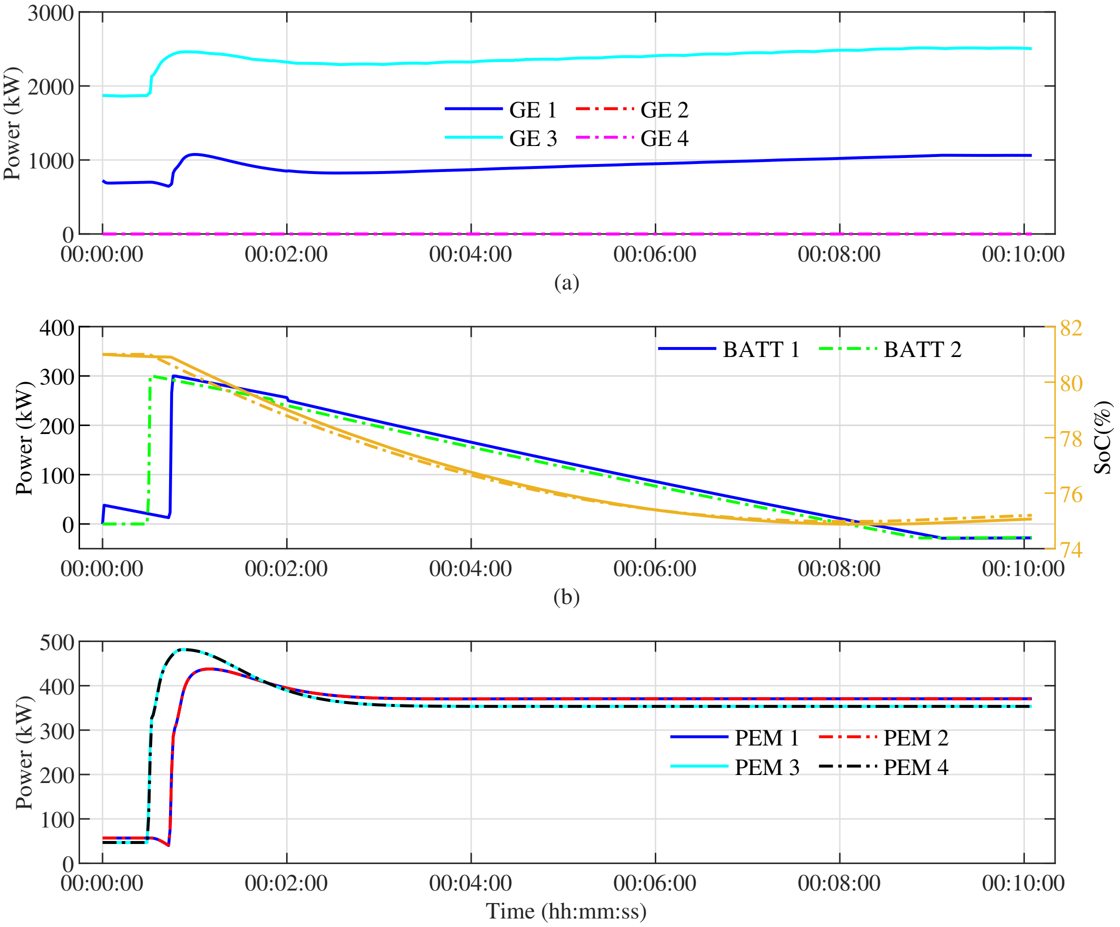
Figure 3: Simulator user interface illustrating DF generator engine operating on gas (left) and battery systems, BMS and EMS (right).

3 Simulation Scenarios

As the developed simulator is a full-scale simulator consisting of major subsystems for power and propulsion system, various simulation scenarios can be developed and presented. However, since the hybrid power system has been the focus in this paper, three different simulation scenarios are developed mainly to exemplify ability of battery systems in supporting dual fuel generators and stabilize them during the normal operation and in the occurrence of a failure.

3.1 *Hybrid Power and Propulsion Scenario*

In this modeled power system, the DF engine generators are major power sources used to generate required propulsion and auxiliary power. In addition, the power system is equipped with two battery systems to assist the generator sets for improved performance as shown in Fig. 4. Initially, generators are supplying the power demand by propulsion and auxiliary consumers. The batteries are adequately charged (around 81% SoC) and are in standby position. Due to the sailing conditions, the operator at the bridge moves port and starboard levers ahead demanding more power in both propellers. It resulted in sudden increase in PEMs power, which is then supported initially by the batteries. Later, battery load is transferred gradually to the generators, which took around 7 minutes. SoC of batteries decreased from around 81% to 75%. When total battery load is transferred to the generators, batteries start consuming some generator power to slowly charge up to 80% SoC which is a default SoC set point. However, in case it occurs a new load variation, batteries will act to reduce the sudden effect of load variation to the generators.



(a)

(b)

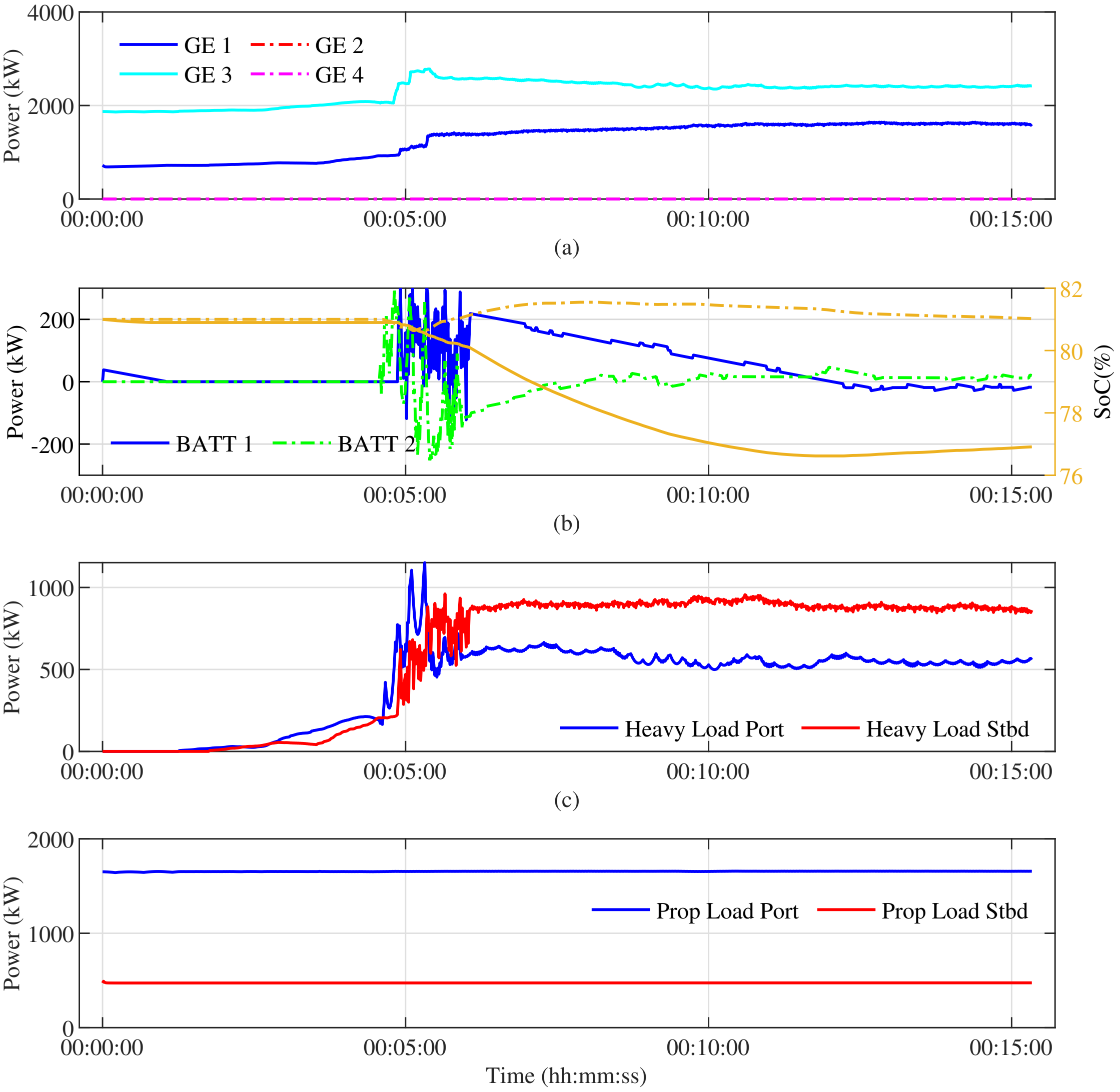
(c)

Figure 4: Simulation results illustrating the battery assistance to the generators in sudden increment of propulsion power demand. (a) Generator power (GE 1/2/3/4). (b) Battery power (BATT 1/2). (c) Propulsion electric motor power (PEM 1/2/3/4).

3.2 *Power System Stabilization Scenario*

Another functionality of a battery in a shipboard power system is to enhance power system stability. Due to the environment or nature of the components, electrical load onboard a vessel can be fluctuating. These fluctuating loads can easily make the power system unstable, leading to the blackout situations or create the safety issue. Therefore, it is necessary to handle the fluctuating loads. As the big engine and generators usually have higher time constants, they may not be able to respond such fluctuating loads. However, battery systems, having much faster response time than the generator sets, can respond these loads. In this simulation scenario, generators are supplying the total propulsion load at port and starboard sides as shown in Fig. 5. Later, heavy loads such as re-liquefaction and VOC (volatile organic compound) pumps and compressors are started. These heavy loads began to fluctuate significantly at around 5 minutes of sailing, which are effectively handled by the battery systems onboard.

This resulted in very less fluctuations in the generator power, thereby enhancing the power system stability and safety. Besides, it also decreases the maintenance cost of the rotating parts as it reduces wear and tear in engine and generators.



(a)

(b)

(c)

(d)

Figure 5: Simulation results illustrating the battery contribution to reduce impact of fluctuating load on the generator sets. (a) Generator power (GE 1/2/3/4). (b) Battery power (BATT 1/2). (c) Fluctuating heavy Loads (d) Stable propulsion load.

3.3 Worst Case Failure Scenario

As the modeled ship for this simulator is DP class 3 type, it has the required power system redundancy. The control system is also equipped in such a way that it can handle the sudden failure conditions without compromising the ship position and heading. In this simulation scenario, DP / Maneuver operational mode is selected, and the configuration is set to auto mode. It enables the load dependent start stop limit calculation that takes care of WCF, meaning it starts and connects the generator(s) in a bus to ensure the sufficient available power required for the propulsion in case failure condition occurs. To demonstrate WCF-based scenario with a two split power system configuration, generator start power limit for the port and starboard side together with the thruster, batteries, generator power, and bus-tie breaker positions in each side are shown in Fig. 6. The PEMs are operating, and their power level are not altered in this simulation scenario. Similarly, generators 1 and 3 are supplying the existing propulsion and auxiliary power demand.

At around 1 minutes and 30 seconds, the bow azimuth thruster 2 lever position is moved forward, which demanded the increased electrical power at the port side. Since the battery 2 was in standby, it took over the increased load demand initially and slowly transferred the load to generator 1 as it had sufficient available power.

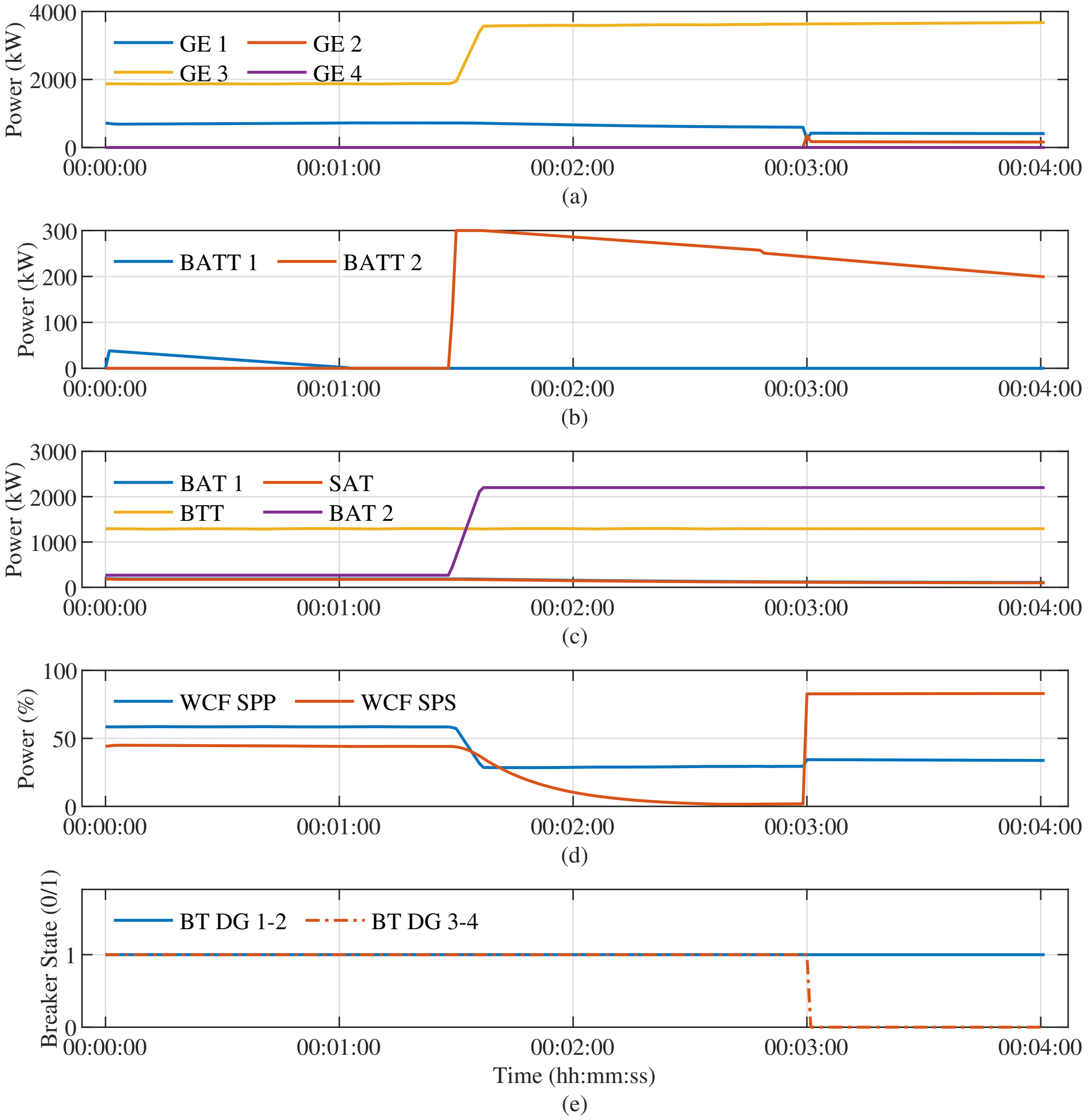


Figure 6: Simulation results illustrating WCF-based load dependent generator start test. (a) Generator power (GE 1/2/3/4). (b) Battery power (BATT 1/2). (c) Bow azimuth thruster (BAT 1/2), stern azimuth thruster (SAT), bow tunnel thruster (BTT) power. (d) Worst case failure start power limit port or starboard side (WCF SP(P/S)). (e) Bus-tie breaker states (BT (GE 1-2 / GE 3-4)).

However, this event resulted in recalculation of WCF-based load dependent start of generators. As the load in port side increased, the WCF start power limit port (SPP) and start power limit starboard (SPS) decreased. The WCF SPS decreased below 10%, initiating the start timer of 60s. Since the WCF SPS is still below 10% even after 60s, generator 2 is started in the starboard side and WCF SPS increases to around 80%. Once the generator 2 is connected to the bus, the starboard side has sufficient available power even if WCF occurs in the port side, however, both the generators in starboard side are then operating in the low load conditions. Further, bus-tie breaker(s) between the generators 1 and 2 are automatically opened resulting into the three split power system configurations.

4 Discussion

This work modeled and simulated the battery hybrid power system in a shuttle tanker, which is a fairly complex power system consisting of dual fuel generator sets, battery systems, AC switch board, DC switchboard, azimuth thrusters, propulsion electric motors, and so on. The simulator has been able to reflect various scenarios onboard a vessel with a realistic behavior. The used models in this simulator are mostly modular, flexible, and scalable such that they can be used to developed various system models appropriate for other ship types.

Besides, the maritime industry has been extensively searching and experimenting on various greener fuel types and the technologies to reduce emissions and improve efficiency ABS (2020). Similarly, reduction of maintenance and operational cost has also been the focus while keeping intact the safety and stability. Battery-based hybrid power system can be considered as one of the greener technologies that can support the maritime industry towards a sustainable future.

The energy efficiency improvement and emissions reduction through battery hybridization is discussed in Miyazaki et al. (2016), which highlights various operational modes of the battery system to achieve the objectives. However, there can be various factors that affect the efficiency and emissions, such as mission profile, weather conditions, operating modes, battery capacity, control strategy, power system architecture, and so on. A simulation-based study done for a cruise ship scenario with a real operational profile (Ghimire et al., 2021c) shows that battery-hybridization improves the energy efficiency in both AC and DC power system architectures. It also showed that battery hybridization improves energy efficiency in rough sea compared to calm sea.

Further, (Ghimire et al., 2024) investigated the impact of battery-hybridization in four different ship types - cruise ship, Ro-Pax ferry, bulk carrier, and container ship with their real operational profiles and three different control strategies. The study showed that fuel saving is achieved by battery hybridization in all ship types. However, it also showed that proper control strategy selection is imperative to improve fuel saving and emissions reduction. It also conducted a brief techno-economic analysis to investigate the viability of battery hybridizing the existing ship power system. It arguments that proper battery size selection, such as a battery system that can supply almost the same power as an existing generator but only for an hour, make it both economically and technically feasible as one of the generators can simply be replaced with the proposed battery system.

Hence, battery-based hybrid power system can be considered as one of the technologies that can support sustainability in the maritime industry as it increases efficiency and reduces emissions in general. Therefore, implementation of battery systems onboard a vessel is increasing both in the new ship builds and in the retrofits (DNV, 2021). As the battery system is relatively a new technology in maritime industry, it also requires effective tools for design, development, testing, and training. Therefore, the developed simulator can be the effective tool (Kongsberg Digital, 2023).

5 Conclusion

In this paper, a state-of-the-art full scale simulator for a shuttle tanker is developed with a focus on the power and propulsion systems. The modeled shuttle tanker simulator consists of sophisticated power system (a battery-hybrid power system with DC and AC main buses, DC-AC grid converters, and redundant power and propulsion systems). The simulator is developed integrating the dynamic physics-based models for the components onboard. Similarly, it has also simulated the control and automation systems. The simulator is modular and flexible to be interfaced with navigation, cargo simulators and DP control system.

This work demonstrated the simulation scenarios highlighting the impact of battery systems in the power and propulsion systems. It is observed that the battery system enhances the power system stability even in the presence of highly fluctuating loads. It also discussed and demonstrated the power system capability to ensure safety during the DP operation using the worst-case failure-based load dependent start stop limits for the dual fuel generators. Moreover, this work exemplifies the recent efforts in maritime industry towards implementing more sustainable ship power system (incorporating battery systems, AC and DC buses) as well as its commitment in safe DP operations.

Further, being a committed sustainability partner organization in the maritime industry, the future research and development work includes full-scale simulators development for various ship types with greener energy and technological possibilities. This will not only help to train the crew onboard a vessel but also enhance the design, development, and testing phases of the new builds using upcoming greener fuels and technologies.

A Specifications for a shuttle tanker simulator.

Particulars	Specifications
Propeller Speed	83.1 rpm (max)
PEMS 1 & 2	3.25 MW (each)
Generator Set 1 & 4	4200 kW (each)
Generator Set 2 & 3	5600 kW (each)
Gas Turbine	1000 kW
Thruster (3 azimuth and 1 tunnel)	2222 kW (each)
AC Main Bus	690V, 60 Hz
DC Main Bus	1000 V
Batteries	1000 V, 303 kWh (909 kWh max)

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