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Hardware-in-the-loop testing of a battery energy storage controller for harbour area smart grid: A case study for Vaasa harbour grid

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Abstract

A battery energy storage controller (BESC) can balance the mismatch of power demand and supply and improve flexibility and resiliency of seaport microgrids. However, it is required to test functionality of the BESC, and validate that it can balance the power supply–demand imbalance by charging and discharging the battery. The main objective of this study is to implement hardware-in-loop (HIL) tests for validating the controller's functionality. This article investigates the testing performance of the BESC that will be used in harbour grids to adjust for the mismatch of power supply and load demand by appropriately charging and discharging the battery energy storage system. The proposed BESC can effectively save energy and reduce peak load demand in harbour grids with limited transmission and distribution network power capacities. The BESC is initially developed offline in MATLAB/Simulink and then implemented in a FPGA based external controller interfaced with the OPAL-RT real-time simulator by using the IEC61850 communication protocol and GOOSE messages. The BESC is configured and implemented on the external FPGA board. In addition, real data from the local distribution system operator Vaasan Sahkoverkko and the harbour operator Kvarken port of Vaasa have been utilized to evaluate the efficacy of the suggested control algorithm for the battery energy storage system with a realistic scenario. The simulation findings indicate that the BESC can balance electricity demand within the microgrid by charging and discharging batteries.

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Keywords: Battery Energy Storage System; Hardware-in-loop; Harbour grid; IEC61850 standard; Microgrid; Power Control; Real-Time (RT) Simulation

1. Introduction

The global transportation is mainly by ships, and the recent study found that greenhouse gas emissions from ships has raised by 9.6% in 2018 compared to 2012 [1]. In order to meet load demand, typical ships docked in harbours use auxiliary diesel engines and expensive fossil fuel for electric power generation. This results in the producing air pollution, greenhouse gases, and toxic pollutants, which adversely affect the living beings surrounding

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the harbour [2]. The International Maritime Organization (IMO) [1] and the European Union Emissions Trading System (EU ETS) [3] have established a number of strict guidelines and challenging goals for the implementation of appropriate actions to reduce air emissions and enhance the energy efficiency design index and energy efficiency operational indicator. Onshore power supply for the berthed vessels is one of the suitable solutions in this regard [4], however it may raise the power and energy demand of harbour grids [5]. The conventional ships are moving toward contemporary electric/hybrid ships [6] with the main goals of being able to reduce environmental pollution, save fuel, and improve energy efficiency of marine vessels when they are manoeuvring and docking at berth. Modern electric and hybrid ships need electricity for a variety of purposes such as onboard power supplies, battery charging systems, and other loads [7]. These contemporary ships have to monitor and manage the electricity of the shipboard microgrids while using hybrid shipboard power systems, which include battery energy storage devices [8]. In order to meet the increasing power and energy demand in harbour grids, renewable energy sources along with energy storage systems, particularly battery energy storage systems, can be quite helpful.

The efficient and environmentally friendly operation of modern ships has paved the way for the development of harbour area smart grid (HASG) [4], seaport microgrid [6], wise ports [9], smart ports [10], and integrated port energy systems [11]. The electric ships require efficient onshore power, which includes a communication network along with a utility grid and energy storage system [12]. Power is supplied to these ports by a seaport microgrid that uses renewable energy sources and battery energy storage technologies in addition to the main grid. Power balancing within this port microgrids, detection of microgrid islanding, and a seamless transition from grid-connected to islanded mode are just a few of the challenges that must be considered while designing seaport grid. It is also necessary to keep the onshore power supply's voltage and frequency compliant with the High Voltage Shore Connection (HVSC) specifications [13]. In addition to these constraints, it is crucial to consider shore-to-ship power supply and battery recharging during the scheduled stay of modern boats when designing these port microgrids [7]. Managing the electrical power and energy needs of modern ports has been a complex task, and the port region is considered a unique territory to manage its own power supply and demand [9]. The authors in [14] have investigated on integration of different types energy storage system in ports and found that use of energy storage system can shave peak-load demand. The primary goal of energy management and vessel scheduling in harbours is to maximize profit gains while minimizing pollution. To this end, a method of optimizing coordinated scheduling for a grid-connected microgrid is proposed for serving a seaport taking into account the uncertainties due to the dynamic nature of renewable energy sources (RES) and load demand [15]. The multi-agent based control system has been utilized in [16] to deal with port energy demand, for example, and this is just one example of the variety of control and optimization strategies that may be used to increase the energy efficiency of these port microgrids [17].

As the demand to move from fossil fuels to renewable energies grows continually, so does the need to design a sustainable and resilient infrastructure that combines alternative energy sources [18]. Battery energy storage system (BES) is frequently used for purposes such as frequency management [19], load shifting, and the integration of renewables [20]. The new approaches to energy system planning, design, and operation have developed out from widespread concerns about the eventual exhaustion of air pollutions from conventional fossil fuel energy resources and its consequential damage to the environment. In the past, power and communication systems were typically developed and verified separately, but today, energy systems are analysed and tested together. When it comes to testing and validating hardware and algorithms in realistic environment, real-time simulation has gained a lot of attention in recent years [21]. In contrast to real-time simulation, typical simulation software tools do not allow for direct interaction with the physical components [22]. Furthermore, the digital real-time simulator, using cutting-edge digital hardware and parallel computing methodologies, can solve the model's differential equations in the same amount of time as the execution time in the actual world [23,24]. This delay in execution is what distinguishes traditional offline simulation software from real-time simulation software. These cutting-edge real-time simulation tools offer a more realistic and cost-effective method for testing and validating the operation of a controller or power system component. A reactive power controller is developed in the beginning using MATLAB/Simulink [25], then to the controller-hardware-in-loop, and after that tested using an accelerated real-time co-simulation platform [26]. Using the IEC61850 generic object-oriented substation event (GOOSE) protocol, a case study of AC microgrid has been examined in a real-time simulator with hardware-in-the-loop testing [22]. This paper is an extension of the previous research [27], where the authors had successfully implemented IEC61850 GOOSE communication standards for controlling the BESC, which is termed as real-time testing of the BESC with simulation-in-the-loop

(SIL). However, in this paper, the authors have implemented the control algorithm of the BESC on FPGA through IEC61850 GOOSE communication standards, which is known as hardware-in-the-loop (HIL) testing of the BESC. Therefore, this research work distinguishes from the previous research work and the main contribution of this study is to evaluate and compare the results of the previous (SIL) testing with the current (HIL) testing of the BESC.

According to the authors' best knowledge and the literature reviewed, there is a need for academic and industrial research to test and validate the performance of the BESC in real-time simulation environments with specialized control functions. This necessitates that a BESC has to be designed and tested in a way that makes it able to handle the specific control challenges. The main objective of this paper is to make HIL test of a BESC for HASG, and verify that it works well with the IEC61850 communication protocol. By charging and discharging the battery energy storage system, this BESC will help control the flow of active power and give the HASG more flexibility. First, the BESC model is made in MATLAB/Simulink. Then, it is transformed so that it can run on RT-LAB software. Then, according to the IEC-61850 standard, the Generic Object-Oriented Substation Event (GOOSE) message is used to send and receive information between the BESC and the IED so that the controlled actions can be performed successfully. The paper is organized as follows. Section 2 describes briefly about the RT-LAB software used to build a model for the Vaasa harbour grid feeder topology. In Section 3, a method is described for developing, testing, and validating the BESC as the HIL in real time simulation. The simulation is based on actual grid information regarding the hourly yearly power consumption of the secondary substations of the Vaasa harbour grid. In Section 3, the results of the simulation are shown, and Section 5 concludes and provides future research directions.

2. Modelling of Vaasa harbour grid

The Vaasa harbour grid topology along with MATLAB/Simulink model in phasor simulation has already been developed in [5]. Accordingly, the developed MATLAB/Simulink model has been transformed to run on RT-LAB software platform, so that the performance of HIL test of BESC can be analysed in OPAL-RT simulation tool. The details of converting MATLAB/Simulink phasor type model into Simulink model for RT-LAB simulation platform, and designing BESC controller along with implemented control algorithm in IEC61850 GOOSE standard using subscribing and publishing methodology has already been provided by the authors in [27]. However, the main focus of this paper is to implement BESC on FPGA and observe its performance. Therefore, this paper contributes in testing BESC with HIL simulation. The Fig. 1 illustrates the partial view of Vaasa harbour grid topology developed in computational subsystem of RT-LAB compatible Simulink model. It consists of main grid power supply, variable load of onshore power supply for the scheduled ferry as well as harbour grid fixed load.

3. Design and testing of BESC using HIL testbed with IEC61850 GOOSE communication

This section presents the procedure of developing the HIL testbed and its implementation for the BESC employed in a realistic case of Vaasa harbour grid.

For the HIL testbed, the functionality of the BESC is developed with following steps:

- Develop the bidirectional communication links for the BESC in line with the IEC 61850 standards
- Develop and design the BESC data object model upon IEC 61850 standard specifications
- Develop "intelligent" BESC controller algorithm based on Boolean logic, which is subsequently implemented at the FPGA controller using C code via LINUX environment.

A star topology for the Vaasa harbour grid communication system setup is used for simplicity, where, the real-time simulator, host PC, and physical IED implementing the BESC (FPGA board) are directly connected to an Ethernet switch enabling interconnection of all entities., According to the star topology, transferring packet delay will be less than other topologies (cascaded, ring etc.). In practice, any entities connected to the switch might subscribe to the published GOOSE packets with lower latency, allowing them to meet the IEC 61850 GOOSE message latency standards (less than 4 ms) set by the IEC 61850 standard GOOSE protocol [28]. However, star topology has one critical point, which is the Ethernet switch, and has no redundancy, that is the drawback of this topology. Therefore, a failure of the switch will result in the failure of the whole communication system.

In the FPGA board implementing the BESC, the proper IEC 61850 GOOSE publisher and subscriber code blocks are designed and configured in order to publish and subscribe the GOOSE message from the OPAL-RT test model. The proposed BESC algorithm programmed on the FPGA board will calculate the mismatched power

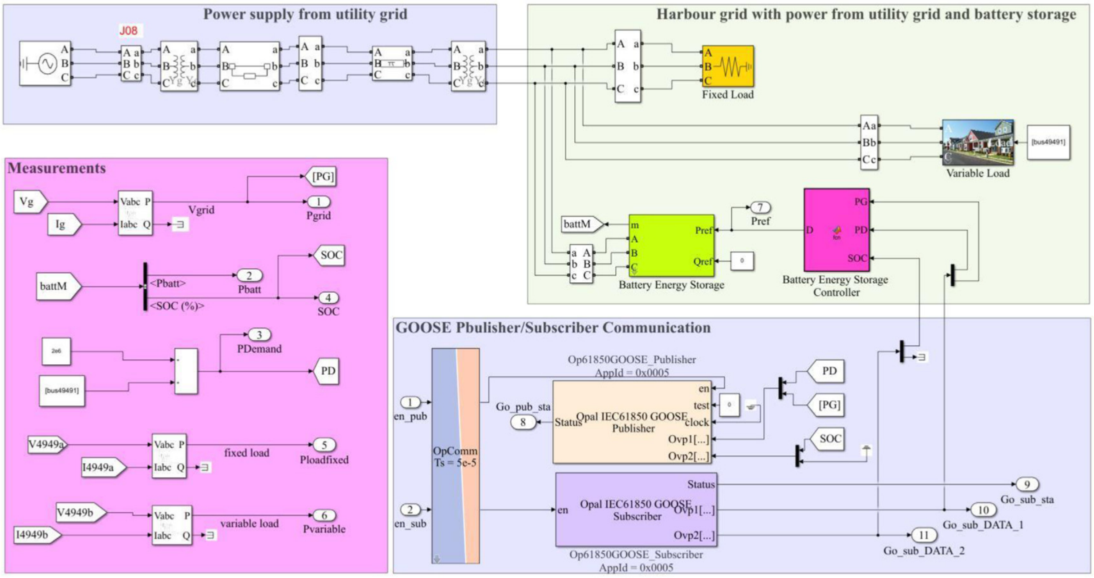

Fig. 1. Computational subsystem model of Vaasa harbour grid [27].

based on the received values of power supply and load demand using GOOSE messages sent to it. During the development process it is verified that the BESC can successfully subscribe to the real-time simulator GOOSE message as illustrated in Fig. 2, where the SSH terminal running the BESC shows the three measurements that are extracted from the received GOOSE messages. In order to be analyse, all these extracted parameters are printed out on the output of terminal and recorded.

In the developed HIL closed loop simulation setup, GOOSE publisher block is added to the model to enable GOOSE publishing and encapsulating the three measured (PD, PG and SOC) values from the real-time simulator (Opal-OP5600) test model to the BESC to be employed for the BESC of Vaasa harbour grid. The BESC implementation need to be developed in a way that it has the ability to subscribe to GOOSE messages coming from the model via the real-physical communication network. Thus, the BESC need to be configured with the GOOSE subscription parameters (MAC address, GOOSE IED, etc.) in a way that it matches with the GOOSE publishing parameters in the simulation model in order to complete the task successfully as illustrated in Fig. 3. The real-time experimental setup, which has been developed in the FREESI lab at the University of Vaasa is depicted in Fig. 4.

The BESC extracts the measurements values from the GOOSE messages and they will be implemented within the BESC control algorithm. The BESC control algorithm originally developed as Simulink blocks needs to be converted to c code in order to be implemented in to the FPGA LINUX environment. The output of the control algorithm is the reference signal. Based on the referenced signal battery is switched between charge, discharge or idle mode as; (Output = 0 => Idle, output = +value => discharge, or output = −value => charge) based on grid power (PG), load demand (PD), and state of charge of battery (SOC). This reference signal is capsulated in another GOOSE message and sent back from the BESC to the real-time simulator via the Ethernet communication network. Inside the real-time simulator model GOOSE subscriber blocks had been added (both GOOSE subscriber old version block based on MATLAB/SMULINK and new version based on OPAL-RT IEC 61850 driver for comparison purpose) and configured to subscribe to the BESC controller GOOSE message that encapsulates the reference value. At this point, after successful subscription, the reference value needs to be extracted from the receiving GOOSE messages and fed to the real-time running model inside the simulator to control the battery operation.

Wireshark sniffing tool has been used to capture the GOOSE traffic and shows the three measurements associated with the captured GOOSE messages and the BESC dispatching GOOSE message with the associated control algorithm output (D parameter). By analysing the messages, it has been verified that the developed BESC is able to subscribe and execute the control algorithm by sending back the output (reference value to the model) with another GOOSE messages. This demonstrates the correct design of the active power management control function and the IEC 61850 data object modelling in this HIL closed loop simulation setup.

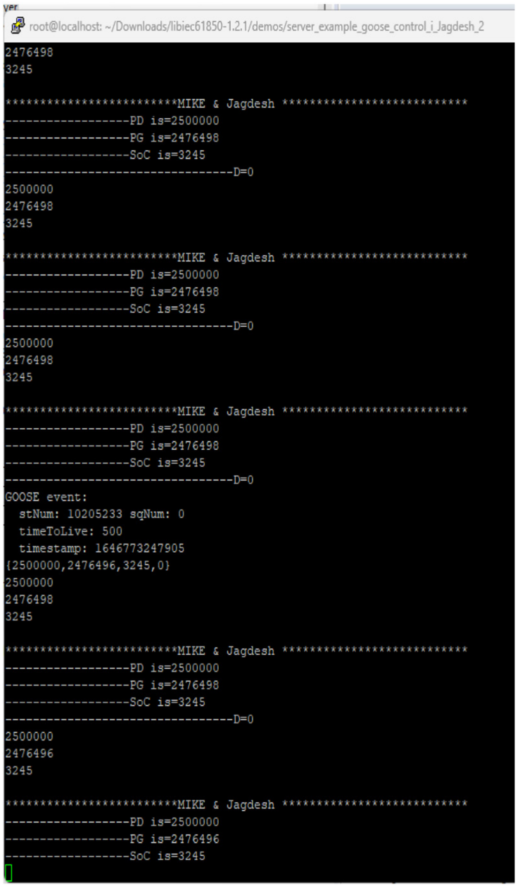

Fig. 2. SSH terminal of IEC 61850 GOOSE parameters and extracted measurements from BESC.

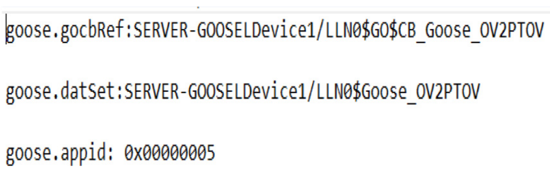

Fig. 3. IEC61850 GOOSE block subscriber parameters.

4. Results

The authors performed several simulations with various scenarios to validate the performance of the developed control algorithm in OPAL-RT HIL simulation. However, three case studies at different states of charges are presented here to show the performance of the BESC. Figs. 5 and 6 show the results of simulations with SOC of battery energy storage system selected initially at 25% and 75% respectively. These two SOCs are selected to see the behaviour of the BESC when battery is near to the limits of the depth of discharge and fully charged. The Figs. 5 and 6 compare the results of the BESC for the HIL simulation with the offline SIL simulation at SOC = 25% and SOC = 75% respectively. Whereas, Fig. 7 illustrates the comparison of the results of reference power (P_{ref}) signals from the HIL simulation and offline SIL simulation results of the BESC at SOC = 30%. The comparison of SOC signals in Figs. 5 and 6 show that the signals from the offline SIL simulation and HIL simulation are the same but with some time delay due to the communication. Whereas, the comparison of P_{ref} signals in Fig. 7 also depicts that the signals from the offline SIL simulation and HIL simulation are almost the same with some

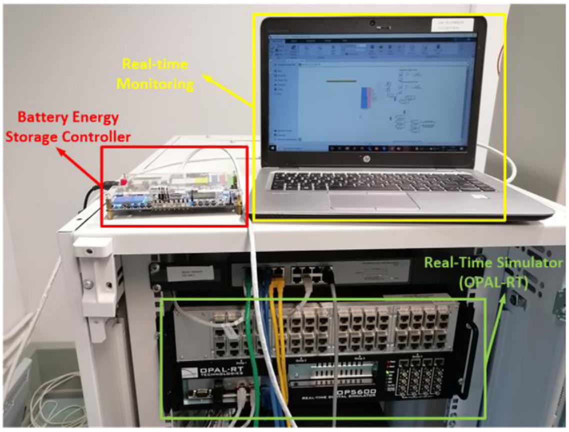

Fig. 4. HiL experimental setup for the BESC implemented in the FPGA board.

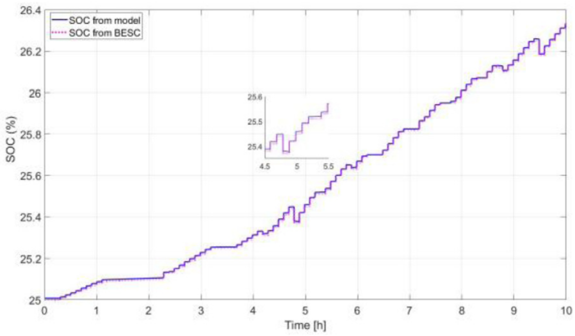

Fig. 5. Comparison of SOC = 25% from BESC and model.

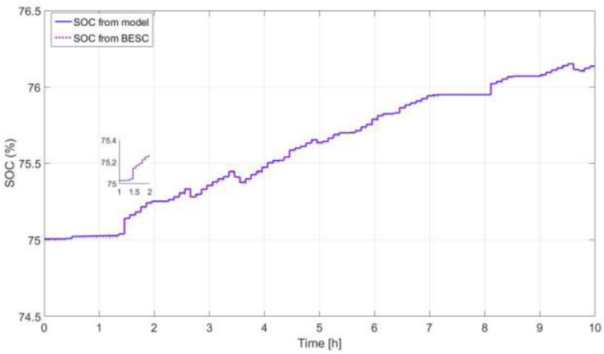

Fig. 6. Comparison of SOC = 75% from BESC and model.

communication delay. Hardware-in-the-loop (HIL) simulations involve physically connected hardware controller with a real-time simulation, and this causes a delayed output response. The delay in outputs from HIL simulation is due to the controller processing time, communication delay, and processing time of inputs and output from real-time simulator (Target). Moreover, the authors have compared all other signals such as PD and PG from the MATLAB simulation model and publisher from the BESC and found the same with some delay due to communication.

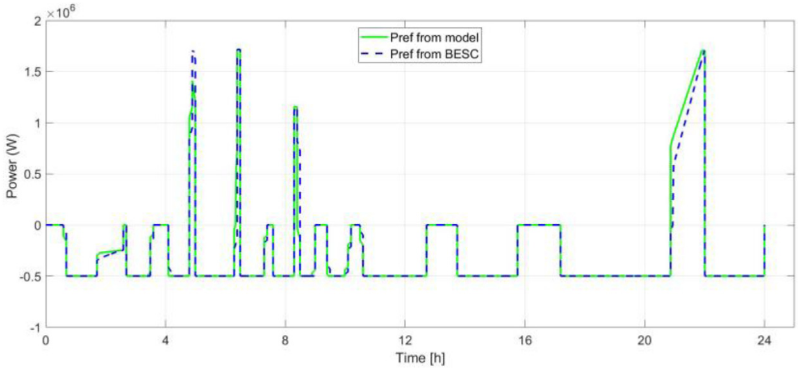

Fig. 7. Comparison P_{ref} from model and BESC.

5. Conclusion

The procedure of developing and validating a battery energy storage controller for harbour grids that handles the scheduled ferry's onshore power supply as well as other harbour grid loads has been the major focus of this research. The model has been developed in the OPAL-RT real-time simulator with GOOSE messages exchanged with the external battery energy storage controller. The rise in power and energy demand at harbours necessitates the implementation of some local power balance at the harbour grid, which is accomplished by incorporating renewable sources of energy and battery energy storage systems. Power and energy demands at the harbour can be efficiently balanced with the best battery energy storage design and management. As a result of this paper, a fully functional HIL testbed for the BESC applying IEC61850 GOOSE communication was implement in real-time HIL simulation. The HIL turned out to be a realistic and economical method for verifying the effectiveness of the control algorithm developed. The authors would like to further enhance the model using load and energy forecasting techniques in the future. They also want to incorporate hardware-in-loop testing in a real-time simulation environment to assess the operation of the seaport microgrid controller that has numerous energy supplies. Future research for seaport microgrids can concentrate on the economic analysis of battery energy investment on the basis of payback time in harbour systems to handle the increasing peak-power demand.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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