Real-time testing of a battery energy storage controller for harbour area smart grid: A case study for Vaasa harbour grid

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***Abstract*— Battery energy storage system makes seaport microgrids more reliable, flexible, and resilient. However, it is necessary to develop, test, and validate the functionality of battery energy storage controller in such a way that it balances power mismatch of demand and supply by charging and discharging the battery. This paper examines the performance of battery energy storage controller (BESC) to be employed in harbour grids in such a way that mismatch of power supply and load demand is compensated by charging and discharging the battery energy storage system. This controller can save energy efficiently and shave peak load demand in harbour grids where transmission and distribution systems have a limited power capacity. The controller of battery energy storage system is first developed offline in the MATLAB/Simulink, and then implemented with IEC61850 communication protocol for publishing and subscribing GOOSE messages. Moreover, to test the effectiveness of the proposed control algorithm of battery energy storage system, a real data from the local distribution system operator Vaasan Sähköverkko and harbour operator Kvarken port of Vaasa has been implemented. The simulation results show that the designed battery energy storage controller can balance power inside microgrid by charging and discharging of battery storage. The applied technique used in this paper is useful to validate the controller functionality in real time with the concept of simulation-in-loop (SIL), which is a practical approach, and it provides a cost-effective way to observe the performance of the controller.**

Keywords—Battery Energy Storage System, Harbour grid, IEC61850 standard, Microgrid, , Power Control, Real-Time (RT) Simulation

I. INTRODUCTION

The vessels are main source of transportation for global trade and most recent study shows that greenhouse gas emissions has increased 9.6% in 2018 as compared to 2012 [1]. The conventional ships staying at harbours employ auxiliary diesel engines and cheap fossil fuel for electric power generation to meet the load demand and it causes air pollutions and produces greenhouse gases and toxic emissions, which are dangerous to living beings surrounding harbours [2]. International Maritime Organisation (IMO) [1] and European Union Emissions Trading System (EU ETS) [3] set some stringent rules and ambitious targets to take some suitable measures to curb air emissions and improve energy efficiency design index and energy efficiency operational indicator. In this regard, onshore power supply [4] for the vessels is considered as one of the appropriate solution, but this may increase power and energy demand of harbour grids [5]. Besides this, the conventional vessels also shift towards modern electric/hybrid vessels [6] with the major purposes being able to reduce environmental pollutions while manoeuvring as well as staying at berth, save fuel, and increase energy efficiency. The modern electric and hybrid vessels staying at harbours require electricity for multiple purpose such as onshore power supply, battery charging systems, and etc. [7]. These modern vessels operating mostly on hybrid shipboard power systems including battery energy storage systems have to control and manage power of shipboard microgrid [8]. Therefore, renewable energy resources and energy storage systems especially battery energy storage system can play a vital role to cope with growing power and energy demand in harbour grids.

The environmental and economic operation of modern vessels enable today's port towards the harbour area smart grid (HASG) [4], smart port [9], wise port [10], microgrid seaport microgrid [6], and integrated port energy systems [11]. The power in these port microgrids is being supplied from seaport microgrid consisting of renewable energy sources, and battery energy storage systems in parallel with main grid power supply. There are several challenges such as balancing of power for the distributed energy resources (DERs) inside these port microgrids during grid-connected mode, islanding detection of a microgrid, and smooth transition of microgrid from grid-connected to islanded mode. It is also required to maintain the voltage and frequency for onshore power supply according to the High Voltage Shore Connection (HVSC) standards [12]. Besides these challenges, maintaining power balance and power quality of these port microgrids is an essential requirement while considering shore to ship power supply and recharging of batteries for the scheduled stay of the modern vessels [7]. The port area is considered as a unique territory [9] and port authorities have to play a vital role because managing power and energy demand of the modern ports have been a challenging task. Improving energy efficiency of these port microgrids is also an other challenging task [13] and for this different control and optimization techniques can be employed such as multi-agent based control energy control system has been used to cope with port energy demand [14].

The great concern over depleting of conventional fossil fuel energy resources and their negative impact of environmental pollutions has driven towards new ways of planning, designing and operating the energy system. Power and communication systems were usually designed and validated individually in the past, but modern energy systems are analysed, and tested with an all-inclusive approach. In this regard, real-time simulation has grasped a great attention during past few years for testing and validating equipment and algorithms in a controlled and realistic environment [15]. The traditional simulation software tools has not the possibility to interact with physical components as in the case of real-time simulation [16]. Moreover, the digital real-time simulator by employing advanced digital hardware and parallel computing methods have capability to solve the differential equations of the models within the same time in the real-world clock and this time is known as execution time [17] [18]. This execution time makes the difference between conventional simulation software tools working offline and real-time simulation tools. In [19], reactive power controller is developed from primary stage of algorithm development in MATLAB/Simulink to controller-hardware-loop, and the testing of this reactive power flow controller has been done in accelerated real-time co-simulation platform [20]. A case study of AC microgrid has been tested in real-time simulator with hardware-in-loop testing by employing IEC61850 generic object-oriented substation event (GOOSE) protocol in [16]. It can be concluded that it is more realistic and cost-effective approach to test and validate the performance of a controller or a power system component with these modern real-time simulation tools.

Up to the best knowledge of the authors and the literature surveyed so far, there is a need of academic and industrial research to test and validate the performance of the BESC with specific control functions in the real-time simulation environments. Therefore, it is inevitable to design and validate a BESC in such a way that it can cope with the specific control challenges. This paper aims to develop and test a (BESC) for HASG and validate its performance with IEC61850 communication protocol. This BESC will be useful to control active power flow by charging and discharging the battery energy storage system and provides flexibility to the HASG. The BESC model is first developed in MATLAB/Simulink and then modified to make it run on RT-LAB software. Moreover, Intelligent Electronic Device (IED) is externally developed for monitoring, supervising and controlling the operation of the BESC. The Generic Object-Oriented Substation Event (GOOSE) message is employed according to the IEC-61850 standard as a bilateral communication between the BESC and the IED for sending and receiving the information to rapidly respond to the controlled actions. The rest of the paper has been organised as follows. Section II presents the model of Vaasa harbour grid feeder topology, which is developed in RT-LAB software. Section III explains a methodology of developing, testing and validation of the BESC as simulation in loop (SIL) in real time simulation. The simulation is based on real grid data of hourly annual power consumption of the secondary substations of Vaasa harbour grid. The simulation results are demonstrated in Section IV, and discussion and conclusion are presented in Section V and Section VI respectively.

II. MODELLING OF VAASA HARBOUR GRID IN RT-LAB SIMULATION

The single line diagram of Vaasa harbour grid topology along with MATLAB/Simulink model in phasor simulation has already been developed in [5]. But, in this paper, the focus is to develop and test the performance of BESC model in real-time simulation. Therefore, previously developed MATLAB/Simulink model has been modified to make it run on RT-LAB software platform, so that the performance of BESC can be analysed in OPAL-RT real-time simulation. For this, the following steps have been taken: previous model has been first converted into discrete MATLAB/Simulink model by replacing or removing some unnecessary blocks and inserting some other required blocks such as communication blocks so that the model can run in OPAL-RT real-time simulation. Other than this, the model has been created with two subsystems namely computation and console subsystems needed by RT-LAB software. The Fig.1 shows the part of Vaasa harbour grid topology developed in computational subsystem of RT-LAB model, which consists of main grid power supply, harbour grid with fixed load and variable load of onshore power supply for the scheduled ferry. The details about designing BESC controller with IEC61850 GOOSE standard has been explained in the next section.

III. DESIGN AND VALIDATION OF BESC WITH IEC61850 GOOSE STANDARD

In this section, we explain that how IEC61850 communication protocol is employed and Generic Object Oriented Substation Events (GOOSE) messages are used for publishing the required information for the proposed battery energy storage controller (BESC). In fact, GOOSE publisher and subscriber blocks were developed to exchange of data into and from the proposed BESC controller. The GOOSE messages control the status of the BESC in such a way that it charges, discharges, or operates in idle mode whenever needed. For this, the IEC 61850 substation configuration description language (SCL) file is developed, and adapted to the software testing platform. The SCL file creates an object-oriented data model for the BESC, which consists of logical nodes (LNs), data objects (DOs), and data attributes (DAs). These LNs, DOs, and DAs are useful for handling and processing measurements data from the “field”, and here in this study, the data is obtained from the simulation model, which has been modelled and simulated using OPAL-RT. Moreover, GOOSE control blocks (GCBs) are developed and configured by building GOOSE data sets. This data set has data attributes which should be associated with the publishing the BESC GOOSE message. The GCB configuration is finalised with GCB parameters such GOOSE ID, GOOSE publishing MAC address, GOOSE subscribing MAC address, GOOSE configuration revisions, etc. Some part of the SCL code has been shown in Fig.2.

Moreover, from the SCL file we creates two files named as static_model.c and static_model.h with generating source codes based on libiec61850 library. The static_model.c file has pre-configured values from the SCL file as well as the definition of data structures for developing IED data model. Whereas, the static_model.h file is included by the designed project code for efficiently accessing the data model. Moreover, data model of each IED type may be mapped to C language data structure based on “model generator” process. In order to provide consistency with IEC61850 standard, the generated C files has to be accompanied with platform-specific code. Thus, BESC control function of charging and discharging has been developed in C language in such a way that it is compatible with software-in-loop (SIL) simulations running with the OPAL-RT eMEGASIM simulator.

BESC will be able to choose the operation mode of battery by subscribing to the GOOSE message sent from the BESC controller which utilizes the measurements from the grid model. After receiving the subscribed GOOSE message with measurements, BESC controller extracts the measurements, and run the control function. Now, the output of the control function is the reference signal (0, 1, or -1) based on grid power (PG), load demand (PD), and state of charge of battery (SOC) as shown in Fig.3. Based on the referenced signal battery is switched between charge, discharge or idle mode of operation.

IV. RESULTS

The simulation was carried out to validate the performance of the developed control algorithm in OPAL-RT real-time simulation and two case studies at different state of charges have been presented in the paper. The authors conducted many simulations with different scenarios but the following results with SOC of battery energy storage system at 25% and 75% have been shown in Fig. 4 and Fig. 5 respectively. These SOCs have been chosen to test the performance of charge/discharge characteristics of the BESC, when the

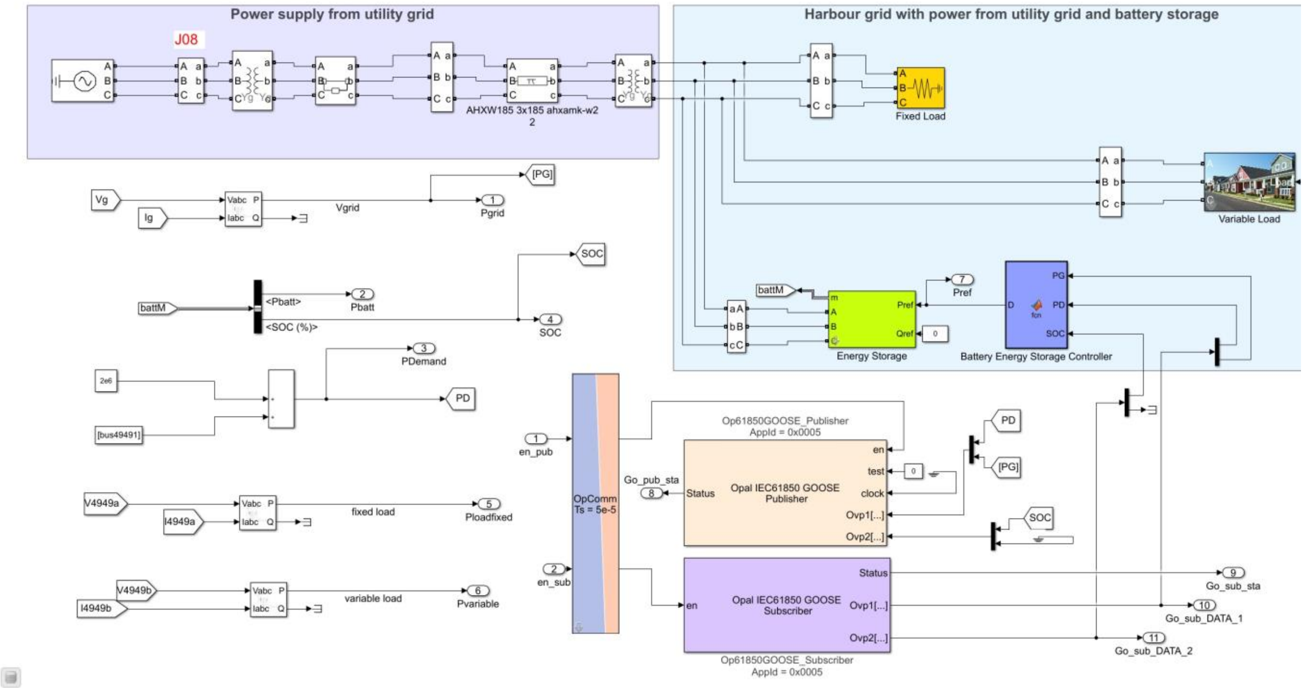

Fig. 1. Computational subsystem model of Vaasa harbour grid

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<Communication>
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   <ConnectedAP iedName="SERVER-GOOSE" apName="SubstationRing1">
     <Address>
       <P type="OSI-AP-Title">1,1,9999,1</P>
       <P type="OSI-AE-Qualifier">12</P>
       <P type="OSI-PSEL">00000001</P>
       <P type="OSI-SSEL">0001</P>
       <P type="OSI-TSEL">0001</P>
       <P type="IP">127.0.0.1</P>
       <P type="IP-SUBNET">255.255.255.0</P>
       <P type="IP-GATEWAY">127.0.0.1</P>

</Communication>
 <IED type="RTUType" manufacturer="OPAL" configVersion="1.0" name="SERVER-GOOSE">
  <Services/>
   <AccessPoint name="SubstationRing1">
     <Server timeout="30">
       <Authentication/>
       <LDevice inst="LDevice1" desc="">
         <LN0 lnClass="LLN0" inst="" lnType="LLN0_0">
          <GSEControl type="GOOSE" appID="Goose_TRIP1" confRev="1" datSet="Goose_TRIP1" name="CB_Goose_TRIP1" desc="For GOOSE_1"/>
          <GSEControl type="GOOSE" appID="Goose_IntVars" confRev="1" datSet="Goose_IntVars" name="CB_Goose_IntVars" desc="For GOOSE_2"/>
          <GSEControl type="GOOSE" appID="Goose_GENPDIF" confRev="1" datSet="Goose_GENPDIF" name="CB_Goose_GENPDIF" desc="For GOOSE_3"/>
          <GSEControl type="GOOSE" appID="Goose_ALLGenTypSup" confRev="1" datSet="Goose_GenTyp" name="CB_Goose_GenTyp" desc="For GOOSE_4"/>
          <GSEControl type="GOOSE" appID="Goose_OV2PTOV" confRev="1" datSet="Goose_OV2PTOV" name="CB_Goose_OV2PTOV" desc="For GOOSE_5"/>

</DataSet>
  <DataSet name="Goose_OV2PTOV" desc="Fictitious Two step overvoltage protection data">
    <FCDA lnClass="PTOV" lnInst="1" prefix="OV2" ldInst="LDevice1" doName="Ovp1" daName="intA" fc="ST"/>
    <FCDA lnClass="PTOV" lnInst="1" prefix="OV2" ldInst="LDevice1" doName="Ovp1" daName="intB" fc="ST"/>
    <FCDA lnClass="PTOV" lnInst="1" prefix="OV2" ldInst="LDevice1" doName="Ovp2" daName="intA" fc="ST"/>
    <FCDA lnClass="PTOV" lnInst="1" prefix="OV2" ldInst="LDevice1" doName="Ovp2" daName="intB" fc="ST"/>
```

Fig. 2. SCL file for BESC

battery is near to depth of discharge and near to fully charged. These simulations were carried out for whole year (8760 hours) with hourly data of a real grid data from Vaasa harbour grid ferry with varying load scheduled onshore power supply and fixed load of Vaasa harbour. However, to clearly present the results only sample of two months (760 hours) have been shown in the simulation results. The Fig. 4, and Fig. 5 show that the sum of grid power (PG) and battery power (PB) at any point of time instant is equal to total power demand (PD). This is to be noted that the maximum power from the grid has limited capacity of 2.5 MW, and the maximum power demand at certain points of time instants is 4 MW. Thus, the remaining net power, which is a difference of PG and PD is employed for charging or discharging the battery energy storage. Moreover, it has been observed that regardless of the initial SOCs of batteries is at either 25% or 75% as shown in Fig. 4, and Fig. 5 respectively, the BESC perform according to the status of current load demand and grid power and gives the output in the form of charge mode, discharge mode, and idle mode of operation. Besides this, the voltage at the buses is also within the specified limits of HVSC standards. The BESC controller perform according to the specified conditions, and it can be concluded with these two case studies that instead of single battery of higher power capacity, total sum of two or more batteries of equal power capacity to that of a single battery at different SOCs can better stabilise grid power and increase power reliability. However, the economic operation and cost analysis of comparison of the single battery with multiple batteries is out of scope of this paper, but it could be and interesting future research work.

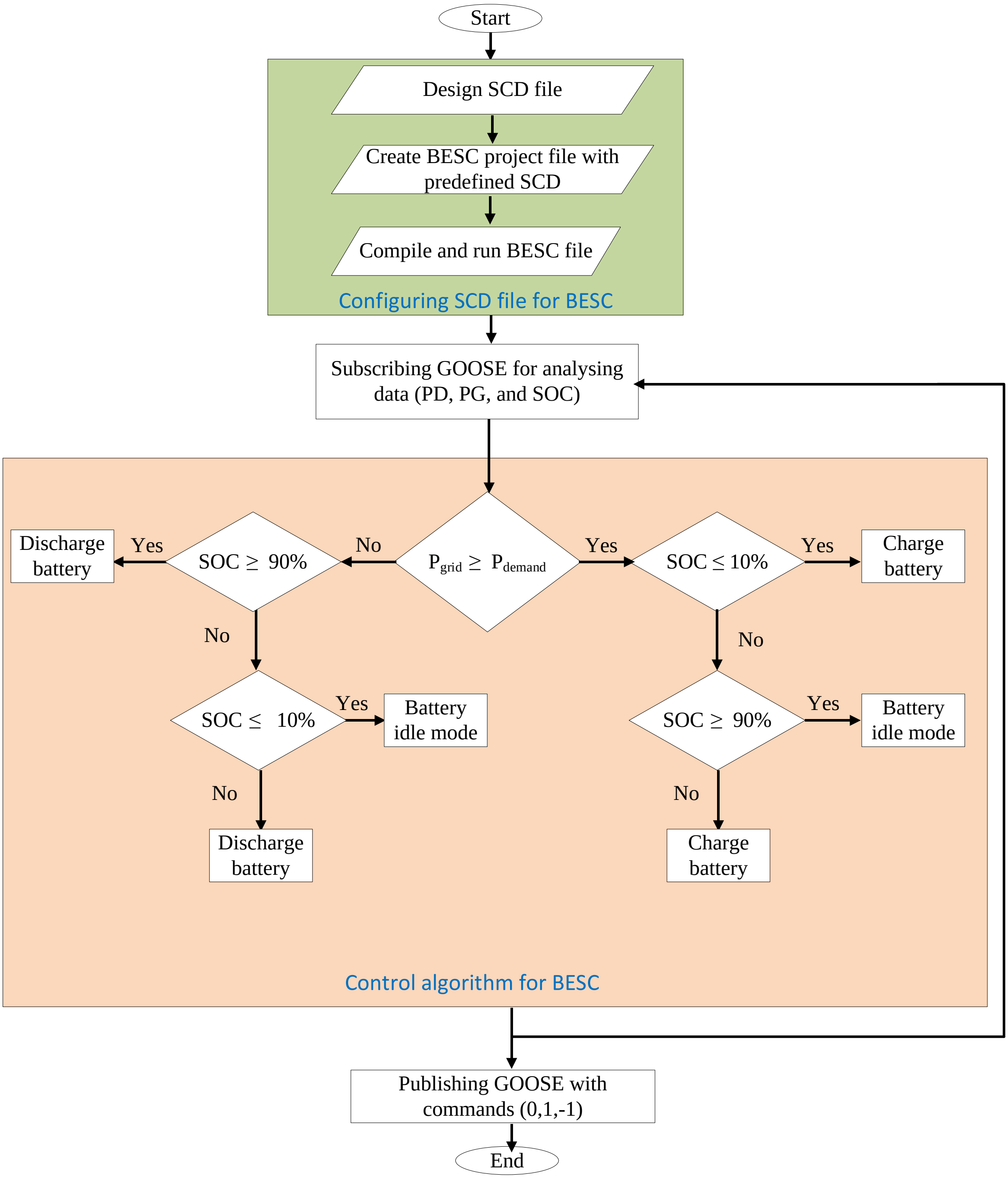

Fig. 3. BESC algorithm using IEC61850 GOOSE message

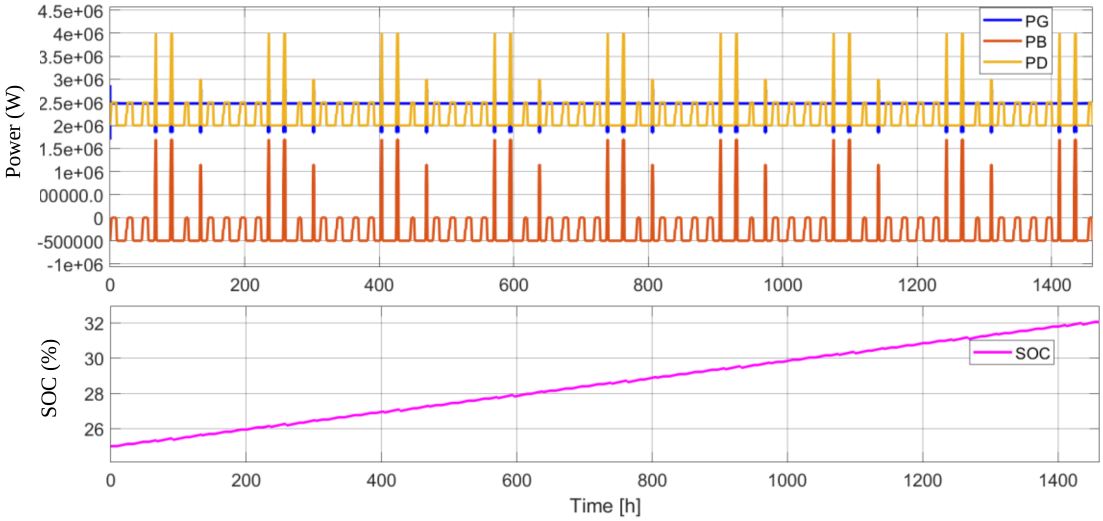

Fig. 4. Battery energy storage at SOC=25%

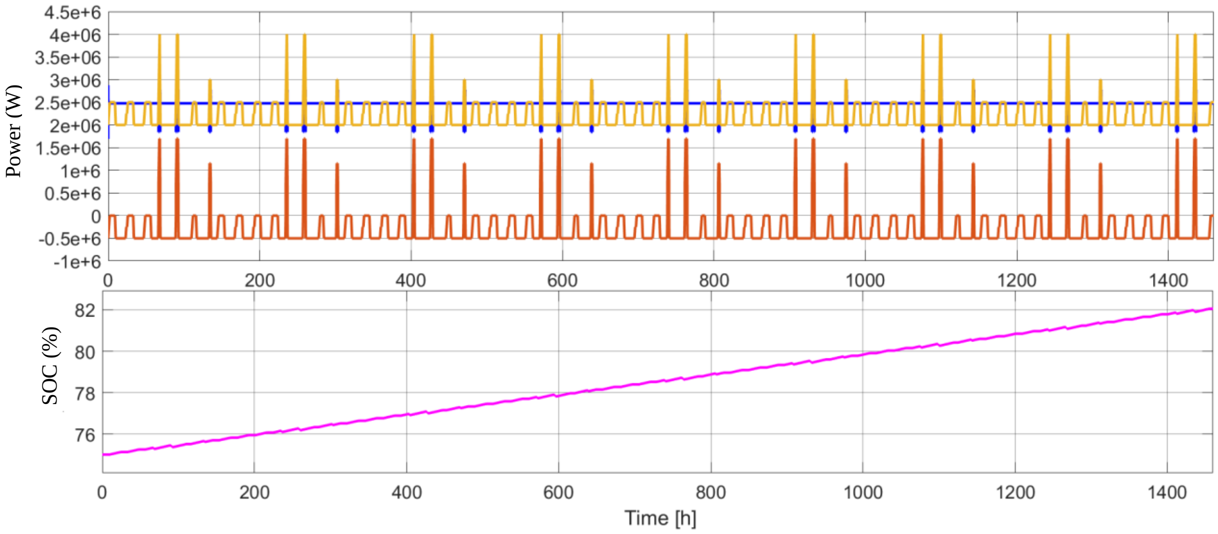

Fig. 5. Battery energy storage at SOC=75%

V. CONCLUSION

This paper has focused on the procedure of designing and validating battery energy storage controller of harbour grids supporting onshore power supply of the scheduled ferry along with other harbour grid loads. The IEC61850 communication protocol has been implemented and the model is developed in OPAL-RT real-time simulator with GOOSE messages as a subscriber and publisher from and to the battery energy storage controller. The power and energy demand at harbours increase, which leads to implement some local power balance at harbour grid with the help of integrating renewables and battery energy storage systems. The optimal design and control of battery energy storage can balance power and energy demands at harbour efficiently. In this regard, this paper has validated the performance of the battery energy storage controller with real data of Vaasa harbour grid, which shows that the balance of active power and local power demand at harbour can be maintained by charging and discharging the battery energy storage system. Thus, the control algorithm implemented with IEC61850 GOOSE standards reduces peak-load demand, and avoid expansion of the existing electrical infrastructure at harbour. This is a reliable and cost-effective way of validating the performance of the control algorithm, and in future, the authors are interested to further develop the model and validate the performance of the battery energy storage controller by implementing hardware-in-loop test in real-time simulation environment. The economic analysis of battery energy investment on the basis of payback time in harbour grids to cope with the growing peak-power demand can be a focus of future research work for seaport microgrids.

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