Jagdesh Kumar

Design and control of harbour area smart grids with application of battery energy storage system

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Tiivistelmä

Maailmanlaajuinen kauppa tapahtuu pääasiassa merialuksilla, ja satamista on tulossa merkittävin osa minkä tahansa maan talouskehitystä. Perinteisten dieselmoottorialusten käyttämä fossiilinen polttoaine aiheuttaa kuitenkin satamissa monenlaisia myrkyllisiä päästöjä ja ilmansaasteita, jotka ovat uhka ihmisten terveydelle ja aiheuttavat monenlaisia vaarallisia sairauksia. Tästä syystä Kansainvälinen merenkulkujärjestö IMO ja EU-direktiivit suosittelevat, että alukset käyttävät satamissa ollessaan maalta tulevaa sähkönsyöttöä tai vähärikkistä polttoainetta myrkyllisten kaasupäästöjen ja ilmansaasteiden rajoittamiseksi.

Tämä tutkimus esittelee uusimpia ja tulevaisuuden merenkulun ratkaisuja, analysoi nykyaikaisten alusten teknisiä vaatimuksia sekä satamaverkkoja ja esittelee uusia malleja satama-alueen älykkäille sähköverkoille, joilla tuetaan maasähkön käyttöä ja akkujen lataamista vaativia aluksia. Tutkimuksessa tarkasteltiin useita akkuenergiavarastojen latauskonfiguraatioita sekä hitailla että nopeilla latausjärjestelmillä sähkö-/hybridialuksille ja analysoitiin niiden käytännön toteutukseen liittyviä teknisiä haasteita. Akkuenergiavarastojen sopivaa kokoa ja sijoittelua satamaverkkojen tehokapasiteetin parantamiseksi selvitettiin todelliseen verkkoon perustuvassa tapaustutkimuksessa, jossa parannettiin Ahvenanmaan verkon satamien tehokapasiteettia. Lisäksi kehitettiin akkuenergiavarastojen ohjausalgoritmi tehotasapainon ylläpitämiseksi Vaasan satamaverkossa ensin MATLAB/ Simulink-mallina, jonka jälkeen sen suorituskykyä testattiin OPAL-RT reaaliaikasimulaattorilla suorittamalla ns. laitesilmukkasimulaatioita.

Ehdotetuilla satamaverkkomalleilla voidaan vastata ilmansaasteista aiheutuviin ympäristöongelmiin sekä mahdollistaa maasähkönsyöttö ja akkujen latausasemat tuleville hybridi- ja sähköaluksille. Lisäksi tämä väitöskirja voi toimia pohjana uusien liiketoimintastrategioiden kehittämiselle alusten omistajien, satamajohtajien ja paikallisviranomaisten tarpeisiin.

Asiasanat: Akkuenergiavarasto, akkujen latausasemat, päästöt, satamaverkkomallit, meriliikenne, mikrosähköverkko, maasähkönsyöttö, tehonsäätö, uusiutuvat energialähteet

Abstract

Global trade occurs mostly on seaborne vessels, and harbours exist as the most significant part for enabling the economic development of any country. However, the amount of fossil fuels used by conventional diesel-engine powered vessels produce a great number of types of toxic emissions, such as air pollution particles at harbours, which create a threat to human health that can contribute to higher morbidity and mortality rates among humans. Therefore, the International maritime organisation and the European Directives recommend that ships implement methods that limit toxic gas emissions and air pollution, such as using onshore power supply and fuel with low-sulphur content for on-board power generation in vessels while remaining at harbours.

This research presents cutting-edge methods and tools for contributing to the development of future marine solutions and analyses of modern vessel technological requirements as well as harbour grids, and it proposes novel models of harbour area smart grids for facilitating the support of onshore power supply and charging of batteries for those vessels that require it. This research explores the usage of multiple battery-charging configurations with either slow- or fast-charging systems for electric or hybrid vessels, and it analyses the technical challenges that could inhibit or prevent the practicality of their implementation. The suitable size and allocation of battery energy storage systems for real-world case power systems of Åland Islands harbour grid are also investigated to enhance power capacity of harbour grids. Moreover, a control algorithm for the battery energy storage controller was first developed in MATLAB/Simulink for the Vaasa harbour grid, and then its performance was tested in the OPAL-RT real-time simulator by conducting a controller hardware-in-the-loop test to maintain the power balance inside the harbour grid.

The proposed harbour grid models can reduce the degree of pollution that degrades the environment while providing onshore power supply and battery-charging stations for hybrid or electric vessels. Moreover, this dissertation acts as a foundation for developing future business strategies for ship owners, port administrators, and local authorities to solve similar problems as technology develops and environmental degradation continues to be a problem of every country in the world.

Keywords: Battery energy storage system, Battery-charging station, Emissions, Harbour grid models, Marine transportation, Microgrid, Onshore power supply, Power control, Renewable energy resources

I dedicate my work of dissertation to my

Lord Hazoor Baba Krishnanad Ji Sahab,

whose countless eternal mercies and blessings are always with me.

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Vaasa, 09.03.2023

Jagdesh Kumar

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Abbreviations

AC	Alternating Current
AES	All-Electric Ship
BESC	Battery Energy Storage Controller
BESS	Battery Energy Storage System
CC/CV	Constant current/constant voltage
CO2	Carbon dioxide
DA	Data Attribute
DG	Distributed Generation
DO	Data Object
DC	Direct Current
ESS	Energy Storage System
ECM	Equivalent Circuit Model

EU	European Union
FCS	Ferry-Charging Station
FPGA	Field-Programmable Gate Array
GCB	GOOSE Control Block
GHG	Greenhouse Gas
GOOSE	Generic Object Oriented Substation Events
IMO	International Maritime Organization
HIL	Hardware-in-the-Loop
HVSC	High Voltage Shore Connection
IoT	Internet of Things
KBM	Kinetic Battery Models
LIB	Lithium-ion Battery
LN	logical Node
LNG	Liquefied Natural Gas
LVSC	Low Voltage Shore Connection
NOX	Nitrogen Oxides
OPS	Onshore Power Supply
PM	Particulate Matter
PV	Photovoltaic
RESS	Renewable Energy Resource
SCL	Substation Configuration Description Language
SIL	Software-in-the-Loop
SOC	State of Charge
SOX	Sulphur Oxides
WT	Wind Turbine

Publications

I. Kumar, J., Palizban, O., & Kauhaniemi, K. (2017). Designing and analysis of innovative solutions for harbour area smart grid. *2017 IEEE Manchester PowerTech*, 1–6. https://doi.org/10.1109/PTC.2017.7980870.

II. Kumar, J., Kumpulainen, L., & Kauhaniemi, K. (2019). Technical design aspects of harbour area grid for shore to ship power: State of the art and future solutions. *International Journal of Electrical Power & Energy Systems*, 104 (July 2018), 840–852. https://doi.org/10.1016/j.ijepes.2018.07.051.

III. Kumar, J., Memon, A. A., Kumpulainen, L., Kauhaniemi, K., & Palizban, O. (2019). Design and Analysis of New Harbour Grid Models to Facilitate Multiple Scenarios of Battery Charging and Onshore Supply for Modern Vessels. *Energies*, 12(12), 2354. https://doi.org/10.3390/en12122354.

IV. Kumar, J., Parthasarathy, C., Västi, M., Laaksonen, H., Shafie-Khah, M., & Kauhaniemi, K. (2020). Sizing and Allocation of Battery Energy Storage Systems in Åland Islands for Large-Scale Integration of Renewables and Electric Ferry Charging Stations. *Energies*, 13(2), 317. https://doi.org/10.3390/en13020317.

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VI. Kumar, J., Mekkanen, M., Karimi, M., & Kauhaniemi, K. (2022). Real-time testing of a battery energy storage controller for harbour area smart grid: A case study for Vaasa harbour grid. *2022 IEEE/IAS 58th Industrial and Commercial Power Systems Technical Conference (I&CPS)*, 1–6. https://doi.org/10.1109/ICPS54075.2022.9773800.

VII. Kumar, J., Mekkanen, M., Karimi, M., & Kauhaniemi, K. (2023). Hardware-in-the-loop testing of a battery energy storage controller for harbour area smart grid: A case study for Vaasa harbour grid. *Energy Reports*, 9 (January 2023), 447-454. https://doi.org/10.1016/j.egyr.2023.01.068.

Author’s contribution

Jagdesh Kumar is the first and main author of all publications (Publication I-VII), and he has developed main research ideas, and theoretical framework of all publications, defined research methodology and evaluated results for all publications. Moreover, during review process of the publication, he was the main corresponding author and edited the articles at different stages. The specific contributions of each co-author for these publications are presented below.

Publication I: Jagdesh Kumar has developed the main idea of the paper, and contributed in formal analysis, developing methodology, making simulation models, validating the results and writing the original draft. Omid Palizban has contributed through the comments, discussion, and paper revision. Kimmo Kauhaniemi has supervised the work and contributed through comments and

discussions.

Publication II: Jagdesh Kumar has developed the main idea of the paper, and contributed in formal analysis, developing methodology, making literature review, and writing the original draft. Lauri Kumpulainen has contributed through comments, discussion, and paper revision process. Kimmo Kauhaniemi has supervised the work and contributed through comments and discussions.

Publication III: Jagdesh Kumar has developed the main idea of the paper, and contributed in formal analysis, developing methodology, making simulation models, validating the results, and major writing the original draft. Aushiq Ali Memon has contributed in formal analysis, developing methodology, making simulation models, validating the results, and writing one chapter/section of the original draft. Lauri Kumpulainen has contributed through the comments, discussion, and paper revision. Kimmo Kauhaniemi has supervised the work and contributed through comments and discussions. Omid Palizban has contributed through discussions during the review (revision) process of the paper.

Publication IV: Jagdesh Kumar has developed the main idea of the paper, and contributed in formal analysis, developing methodology, making simulation models, validating the results, and major writing of the original draft. Chethan Parthasarathy has contributed in developing methodology, validating simulation results, and writing one chapter/section of the original draft. Mikko Västi has contributed in developing simulation models and discussing the results. Hannu Laaksonen has contributed in formal analysis, funding acquisition, giving comments and making discussion. Miadreza Shafie-Khah has contributed through the comments, discussion, and paper revision. Kimmo Kauhaniemi has supervised the work and contributed through comments and discussions.

Publication V: Jagdesh Kumar has developed the main idea of the paper, and contributed in formal analysis, developing methodology, making simulation models, validating the results and writing of the original draft. Hussain Sarwar Khan has contributed in making simulation model, discussion, and paper revision. Kimmo Kauhaniemi has supervised the work and contributed through comments and Discussions.

Publication VI: Jagdesh Kumar has developed the main idea of the paper, and contributed in formal analysis, developing methodology, making simulation models, validating the results and writing of the original draft. Mike Mekkanen has contributed in developing model and writing one chapter of the paper. Mazaher Karimi has contributed through the comments, discussion, and paper revision. Kimmo Kauhaniemi has supervised the work and contributed through comments and discussions.

Publication VII: Jagdesh Kumar has developed the main idea of the paper, and contributed in formal analysis, developing methodology, making simulation models, validating the results and writing the original draft. Mike Mekkanen has contributed in developing model and writing one chapter of the paper. Mazaher Karimi has contributed through the comments, discussion, and paper revision. Kimmo Kauhaniemi has supervised the work and contributed through comments and discussions.

1 INTRODUCTION

Over 90% of the global trade occurs via marine vessel transportation (International Maritime Organization, 2021) (Sulligoi et al., 2015). Marine transportation plays a vital role in the development of the world economy, and it will triple the extent of its role in 2025 when compared to growth in 2008 (Bailey et al., 2004). Therefore, seaports and harbour grids exist as a vital centre for economic development in many countries. Due to the high power generation of marine vessels, they are considered 'floating power plants'. The power that can be generated by them varies from hundreds of kilowatts to tens of megawatts (Sciberras et al., 2016) depending upon the type of the vessel. Normally, the main propulsion diesel engines generate electric power for the vessels throughout manoeuvring and auxiliary diesel engines while staying at the berth (R. Winkel et al., 2016) (Lee et al., 2013). The fuel used by conventional vessels produces vast amounts of harmful emissions, which negatively affect the health of people who live nearby harbours. Fossil-fuel usage at harbours produces greenhouse gas emissions (GHG), air pollutants such as nitrogen oxides (NO_X), sulphur oxide (SO_X), particulate matter (PM), and noise. Therefore, an appropriate solution to reduce harbour emissions is to pivot usage to onshore power supply (OPS) as recommended by the standard for High Voltage Shore Connection (HVSC) systems, which is published by three organisations unanimously namely the International Electrotechnical Commission (IEC), International Organization for Standardization (ISO) and Institute of Electrical and Electronics Engineers (IEEE) (IEC/ISO/IEEE, 2019).

Vessels remaining at berth usually use electricity for different purposes: cooling, heating, lighting, ventilation, communication, loading, unloading, and hotelling (R. Winkel et al., 2016). While remaining at berth, the process of switching off all vessels' diesel engines and supplying the power to the vessels by onshore electricity is usually termed as 'cold ironing'. It also referred to by different names in the literature such as Shore-Side Electricity, Shore-Side Power Supply, Shore-to-Ship Power, Shore-to-Ship Connection, Shore-to-Ship Electrification, Shore Connection, Onshore Power Supply (OPS), Alternative Marine Power System, Alternative Maritime Power, and HVSC (IEC/ISO/IEEE, 2019) (Quaranta et al., 2012)(J. Prousalidis et al., 2014). In order to avoid any ambiguity in understanding, the abbreviation 'OPS' will be used.

Current shipping technology development trends indicate an increase in hybrid and electrical vessels (Jin et al., 2016). Those vessels will employ an integrated power system consisting of renewable energy sources (RESs), especially photovoltaic (PV) and the wind turbine (WT), for generating electricity and the battery energy storage system (BESS) for feeding electricity on-board and onshore. Moreover, it is claimed that because BESS increases fuel-efficiency and reduces emissions, it will eventually become a substantial part of the shipboard power system of modern hybrid and all-electric ship (AES) (Skjong et al., 2015). Following this development, the harbour grid must be designed to accommodate vessels for the OPS while at berth in addition to charging the batteries for those vessels which require it. Therefore, this doctoral dissertation aims to design novel harbour grid models that cope with stringent emission rules set by the International Maritime Organization (IMO) and EU-Directives (European-Directives) by facilitating electric ships with the OPS, developing battery-charging station configurations, and managing and controlling harbour grid power and energy with battery energy storage systems in harbour grids (harbour-side BESS).

1.1 Objectives of the thesis

Fossil fuel dependency, continuous increase in GHG emissions at harbours, and some technical issues define the main obstacles to global development of conventional ships (European Commission, 2011). Stringent environmental rules set by international organisations promote a paradigm shift away from the reliance of conventional vessels, seaports and harbour grids that contribute to GHG emissions. On the one hand, conventional vessels that rely upon fossil fuels are now being gradually replaced by modern vessels that use BESS as a major part of their shipboard power systems. These modern vessels also require the OPS while staying at berths in harbours. Therefore, seaports endeavour to have the OPS, battery-charging systems and a suitable power and energy management strategy to facilitate all kinds of modern vessels. In this respect, there is a need for designing harbour area smart grid (HASG) in such a way to support the modern vessels with the above-mentioned requirements at seaports. Moreover, the HASG should also comply with current standard requirements. In order to deal with the aforementioned challenges, this research work consists of the following objectives:

- To introduce a novel concept of the HASG so as to facilitate OPS and battery-charging station systems

- To design and model multiple scenarios that include battery-charging infrastructure that can accommodate electric vessels with slow- and fast-charging configurations

- To present a method for the sizing and allocation of harbour-side BESS for integrating large-scale RESs and ferry-charging stations (FCSs) by using data extracted from real-case studies of Åland Islands in harbour grids

- To develop a smart control algorithm and test it in a real-time simulation environment for harbour-side battery energy storage controller (BESC) with a real case studies of Vaasa harbour grid

The above research objectives are successfully achieved, and the results are published in high–impact, peer-reviewed research journals and international conferences.

1.2 Research questions

Shipping technology has been progressing rapidly in the areas of propulsion and power supply topologies (Dale et al., 2015). In the next few years, research and development in the technologies of BESS, power electronics, and information technology can bring in a new era of vessel types by employing facilities that can wirelessly charge batteries (Guidi et al., 2017), as well as make real-time measurements and monitoring of the fundamental ship parameters (Skjong et al., 2015). Modern vessels who have small power capacities and operate entirely on a BESS are known as 'electric vessels', whereas large ships that operate on integrated power systems in addition to BESS, are called 'hybrid vessels' (Rahman & Khan, 2020). These modern vessels require an OPS and battery-charging stations in ports to charge the BESS. The author of this publication formally introduced a concept of HASG in Publication I, and Publication II aims to coordinate multiple RESs along with the main grid supply to optimally balance the power and energy requirements of hybrid and electric vessels that require the OPS, battery-charging stations and other necessary loads at harbours. Therefore, the main focus of this thesis is to address the following research questions:

RQ1: What are technical design aspects, standards and barriers in designing HASG supporting an infrastructure for both OPS and battery charging?

RQ2: What could be different types of battery-charging configurations of HASG and how to compare them based on specific vessel and harbour grid requirements?

RQ3: How to solve the challenging issue of appropriate battery sizing and allocation at different nodes of the distribution system connected with the harbour grid, that deals with growing power demands and integration of RESs?

RQ4: How to develop, test and validate the performance of harbour-side BESC to accommodate peak-load power demands with an appropriate control algorithm?

Thus, this dissertation provides new knowledge by developing some novel harbour grid models while focusing on the main objectives, which are based on the issues, problems and challenges raised by international environmental regulatory authorities and modern vessels.

1.3 Research Contributions

This doctoral dissertation has the following main research contributions:

- It provides a comprehensive review of state-of-the-art and future marine solutions, and it discusses the technical requirements necessary for designing harbour grids that are capable of supporting both hybrid and electric vessels. It also introduces and develops the novel concept of the HASG. The proposed HASG models can support hybrid and electric vessels with OPS and battery-charging configurations.

- It discusses the technical challenges and practical implementation of various battery-charging configurations in detail and simulates two case studies of slow and fast battery-charging station configurations with separate and the same connection of the OPS respectively.

- It solves the challenging issue of sizing and locating BESS and the integration of RESs to cope with fluctuating power demand at harbour grids that are planning expansion of the FCSs.

- It develops and implements a novel smart battery energy storage control method, which facilitates the charging and discharging of the BESS in the harbour grid to shave peak-load demand, and it is validated by its performance in real-time simulation with software-in-the-loop (SIL) as well as hardware-in-the-loop (HIL).

1.4 Outline of the thesis

This dissertation comprises seven chapters of the summary section and the appended original research publications. A brief description of each chapter is given as follows:

Chapter 1 introduces the topic, describes the main objectives, investigates research questions, addresses research contributions and presents a dissertation outline and summary of the research publications.

Chapter 2 presents a theoretical background, literature review, state-of-the-art and future marine solutions concerning the design and control of the harbour grid.

Chapter 3 explains technical design aspects, standards and challenges for developing harbour grids supporting the OPS and battery-charging systems for hybrid and electric vessels.

Chapter 4 describes battery-charging methodologies, develops new harbour grid models with different types of battery-charging station configurations, and compares them based on technical challenges. It also presents concepts of slow and fast battery charging when batteries are charged either onshore or on-board.

Chapter 5 highlights the role of accurately sizing and allocation of harbour-side BESS while integrating RESs for future harbour grid design.

Chapter 6 develops a control algorithm for charging and discharging of harbour-side BESC and tests its performance with the SIL as well as HIL by employing OPAL-RT software.

Chapter 7 discusses the main findings and outlines future paths of development.

Chapters 3 to 6 have been allocated for the main research objectives, as shown in Table 1. Each chapter answers either one research question, and one or multiple research papers referred to in each chapter has also been published. A total of seven research papers (Publications I–VII) have been published for this dissertation, for which one author has is responsible.

Table 1. Publications allocated for dissertation chapters

Contribution chapters	Publications allocated to chapters
Chapter 3 (RQ1) Technical design aspects of harbour area smart grids	Publication I: "Designing and analysis of innovative solutions for harbour area smart grid ", *IEEE PowerTech, Manchester, UK, 2017* Publication II: "Technical design aspects of harbour area grid for shore to ship power: State of the art and future solutions", *International Journal of Electrical Power & Energy Systems 104 (2019) 840-852*
Chapter 4 (RQ2) Design of harbour grid models with various battery charging station configurations	Publication III: "Design and Analysis of New Harbour Grid Models to Facilitate Multiple Scenarios of Battery Charging and Onshore Supply for Modern Vessels", *Energies 2019, 12(12)*
Chapter 5 (RQ3) Sizing and allocation of battery energy storage system along with renewables in harbour grids	Publication IV: "Sizing and Allocation of Battery Energy Storage Systems in Åland Islands for Large-Scale Integration of Renewables and Electric Ferry Charging Stations", *Energies 2020, 13(2),*
Chapter 6 (RQ4) Smart control and real-time testing of battery energy storage system for harbour grids	Publication V: "Smart control of battery energy storage system in harbour area smart grid: A case study of Vaasa harbour", *IEEE EUROCON, Lviv, Ukraine, 2021* Publication VI: "Real-time testing of a battery energy storage controller for harbour area smart grid : A case study for Vaasa harbour grid", *IEEE Industrial & Commercial Power Systems, Las Vegas, NV, USA, 2022* Publication VII: "Hardware-in-the-loop testing of a battery energy storage controller for harbour area smart grid: A case study for Vaasa harbour grid", *Energy Reports Journal 9 (2023) 447-454*

1.5 Summary of publications

Publication I proposes an innovative design concept of the HASG that enables OPS to support electric and hybrid vessels of future technology. The designed HASG is modelled using PSCAD software, and the simulation case studies have been carried out to validate its performance in steady and transient states.

Publication II presents state-of-the-art and future marine solutions, discusses OPS technology with respect to voltage, frequency, power and other technical requirements of both vessels and the harbour grid. Moreover, this paper contributes to designing suitable models for the HASG that can facilitate both the OPS as well as the charging of batteries for the future hybrid and electric vessels. This paper explains why an OPS is necessary, how the OPS can be clean and sustainable, and why the OPS is an appropriate solution even if national grid electricity is more expensive and pollutant compared with electricity generated from ship's auxiliary diesel generator.

Publication III explains how to develop and analyse different harbour grid configurations that can facilitate the charging of batteries for modern vessels and the OPS. This paper presents a comprehensive overview of battery-charging configurations and discusses the technical challenges of each design from the perspective of their practical implementation both on-board and onshore.

Publication IV describes the importance of integrating RESs to cope with the growing demand for OPS and battery-charging stations for modern ships. However, sizing and allocating BESS for any operational harbour grid to compensate for the fluctuating power supply from RESs as well as meet the predicted maximum load demand without expanding power systems is necessary.

Publication V develops the harbour-side BESC for optimally controlling and managing the power requirements of the HASG. This paper presents a practical approach where a charge or discharge strategy is applied in such a way that peak-load demand of harbour grid is shaved off by discharging the battery during peak demand load and charging it during off-peak load demand. The Vaasa harbour grid model along with a control algorithm is developed in MATLAB/Simulink for the power flow to and from BESS by charging and discharging through bi-directional DC–DC converter.

Publication VI tests and validates the functionality of the previously developed control algorithm of harbour-side BESC. The previously developed MATLAB/Simulink model was first modified to make it run on RT-LAB software platform, and then the performance of harbour-side BESC is analysed in OPAL-RT real-time simulation.

Publication VII implements the HIL test for validating the functionality of harbour-side BESC. 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 BESS.

2 THEORETICAL BACKGROUND

This chapter contributes to providing theoretical background, comprehensive review of state-of-the-art features of vessels, and technical requirements for designing harbour grids that are capable of accommodating hybrid and electric vessels. This chapter suggests that future marine solutions and future research directions should steer toward focusing on the requirements of modern electric and hybrid vessels associated with harbour grids. It also highlights the positioning of the publications of this dissertation in relation to the research activities in this field over the past years.

2.1 Background and motivation

Global trade mostly occurs via maritime transportation, which heavily contributes to world-wide economic development. Maritime transport mainly includes the usage of vessels and harbours. Conventional vessels operating on diesel engines during voyages or staying at berths in harbours are employing cheap quality fossil fuels that contribute to pollution (NO, SO and PM), vibration, noise pollution, GHG emissions, global warming and climate change. These harmful GHG emissions cause many diseases such as asthma, lung cancer, heart attack and respiratory diseases in humans. The fourth IMO report showed an increase in GHG emissions from overall shipping by 9.6% from 2012 to 2018 (IMO, 2021). Therefore, adverse environmental impact caused by fossil fuels, dependency on fossil fuels, depletion of fossil fuels resources, and rising prices of fossil fuels lead to shift towards alternate energy resources for ships (European Commission, 2011) (Roy et al., 2021) (European Commission et al., 2018) (Jiao & Wang, 2021). In this regard, the IMO (International Maritime Organization, 2021), the EU-Directives (Directive 2005/33/EC Of the European Parliament and of the Council, 2005), and the EU commission (European Commission, 2016) come up with new stringent rules, regulations, and policies to encourage and promote modern vessels having higher energy efficiency and reduced emissions and lower dependency on fossil fuels.

Conventionally, vessels that utilise diesel engine as their main source of manoeuvring and propelling power also may use auxiliary diesel-engine power while ships dock at harbours for different purposes, such as lighting, loading, unloading, cooling, heating, ventilating, etc. (R. Winkel et al., 2016). In order to comply with the current emission reduction regulations set by the IMO, EU-Directives and the EU commission, the ships are required to either use low-sulphur light fuel oil instead of traditional sulphur-rich heavy fuel oil or scrubber technology, which is an attractive option for large vessels (Lindstad et al., 2017) (Abadie et al., 2017). Besides, other options for emission reduction, the OPS is an effective solution to reduce emissions from vessels berthed at harbours. The OPS is the process of switching off auxiliary diesel-engine power generated by vessels and supplying power from the harbour grid. Therefore, there is an utmost need to design harbour grids in such a way that they can adhere with environmental emission reduction requirements (Nuchturee et al., 2020) (Vicenzutti & Sulligoi, 2021), accommodate modern all-electric and hybrid ships' requirements of the OPS and battery-charging infrastructure (Fang et al., 2020), and also adhere to the technical HVSC standard requirements (Fabio D'Agostino et al., 2021). The authors Fang et al. (2020), and Sun & Qiu (2022) mention that the research on designing a harbour grid is limited. Other than Publication I of this dissertation, only one other publication by Ahamad et al. (2018) has simulated seaport microgrid that include ships at berths supplied with OPS. The authors Wang et al. (2019) have acknowledged that innovative design of HASG supporting modern vessels for OPS has been introduced in the Publication I. Moreover, the report by the European Commission (2018), Jiao & Wang (2021), and Fang et al. (2020), highlight Publication II of this thesis as an outstanding review paper. Publication II presents a comprehensive review of technical features, existing standards and challenges of designing harbour grids requiring the OPS as well as battery-charging infrastructure.

2.2 Literature review

Typically, harbours and seaports are located near urban areas, requiring special attention to mainly protect the climate and air pollution issues that cause serious health problems and pose a threat to living creatures. Figure 1 shows the research areas, which are primarily advancing to appropriately design and control the HASG. These research areas include environmentally friendly technologies employed for HASG, modern vessels' requirements from HASG while staying at berth, technical challenges and remedies for implementing OPS, power and energy management of HASG with smart control techniques, sizing and allocation of BESS to support harbour girds, optimisation techniques employed for operating HASG, application of digital and internet of things (IoTs) for operating HASG, and development of business models for HASG. Moreover, this dissertation contributes to five out of these eight categories and the publication numbers are placed in Figure 1 to indicate the coverage. In the following Subsections 2.2.1–2.2.8, a more detailed discussion of the relevant research findings in the literature is made according to this classification.

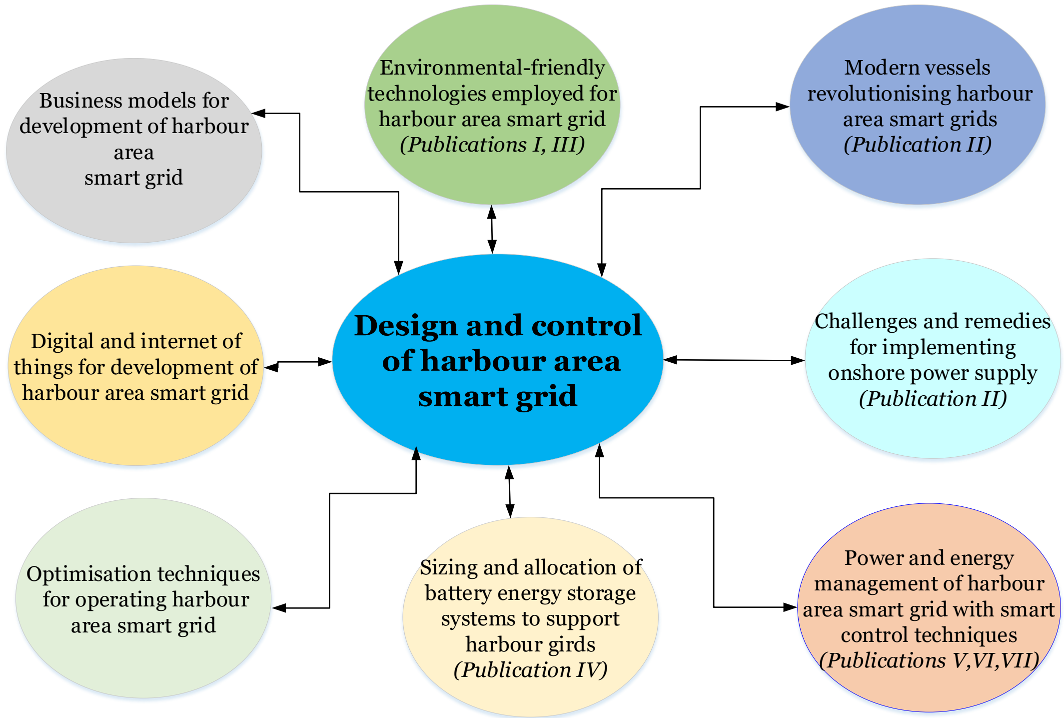


Figure 1. The main research and development progress towards HASG

2.2.1 Environmentally friendly technologies employed for harbour area smart grids

The EU has a carbon neutrality goal to be achieved in 2050 by taking serious actions under implementing the Paris agreement. In this regard, there is also a need to shift towards sustainable and smart mobility by accelerating transition to climate-neutral economy and a toxic-free environment (European Commission, 2021). Finland has a very ambitious target of carbon neutrality, which means that emissions and sinks should have been of the same size by 2035, and Finland has a roadmap to have a faster emission reduction plan to achieve carbon-free transport by 2045 (Finnish Government, 2020). Carbon dioxide (CO_2) emissions produced by maritime transportation causes about 3.3% increase in GHG emissions leading towards global warming and climate change issues (Nuchturee et al., 2020). Therefore, for the reduction for the GHG emissions in marine transportation, there is an utmost need to plan energy transition from fossil fuels and have promising approaches for green energy and eco-friendly technologies for the redesign of ships and ports (Vicenzutti & Sulligoi, 2021). A number of issues confront the global shipping sector, including the need for more environmentally friendly maritime transportation and the application of international legislation to limit emissions (European Commission et al., 2018).

Generally, there are two main legislation bodies namely the IMO and the EU commission for controlling emissions in international shipping transportation (European Commission et al., 2018). EU works with IMO and other international organisations to ensure that high standards for environmental protection, safety, security and working conditions of maritime transportation. By 2050, compared to 2005 levels, CO_2 emissions from maritime transport should be reduced by 40%–50% (European Commission, 2011). Therefore, emissions from shipping transportation can be principally improved with either employing green fuels or OPS, while ships are berthed at seaports (European Commission, 2011) (Jiao & Wang, 2021).

As the modern vessels are equipped with the BESS, harbour grids need to support battery-charging infrastructure at harbours. Publication I presents a novel harbour grid design integrated with RESs facilitating OPS, and Publication III introduces various novel harbour grid configurations to support modern vessels with OPS as well as battery-charging systems. It also discusses details about the technical feasibility of the practical implementation of each configuration. The implementation of these technologies supports the reduction of emissions originating from vessels especially at harbour area.

Gothenburg is the world's first port installed with OPS in 2000 (Yang et al., 2011), which contributes approximately 94%–97% reduction in toxic emissions (Peng et al., 2021). Seyhan et al. (2022) have evaluated the emission reduction in Izmit Bay, Turkey, and concluded that OPS has much more emission reduction impact when applied jointly with an automatic mooring system than separately applying only an automatic mooring system alone. Agostino et al. (2021) report an analysis performed by considering real traffic data and scenarios of penetrating OPS in Italian ports and concluded that OPS has an economic advantage when ports are involved in the energy market, and an environmental reduction impact when the percentage of electrification is also by local power generation by RESs. Therefore, its obligatory use in world-wide scale will have a great impact on reducing the substantial amount of emissions originating from vessels staying at harbours (Peng et al., 2021) (Yin et al., 2020).

2.2.2 Modern vessels revolutionising harbour area smart grids

Modern electric and hybrid vessels are becoming increasingly popular because they adhere to current emission control requirements as well as operate more efficiently (Jin et al., 2016) (Hein, Xu, Wilson, et al., 2021). Besides this, modern vessels use less or no fossil-fuel and have a number of advantages over traditional fuel-powered vessels, including the lowering operating costs by employing energy-efficient methodologies and technologies. As BESS and fuel cell technology continue to improve, it is likely that electric vessels will become more prevalent due to strict emission reduction rules. When berthed at harbours, these vessels have specific requirements in order to maintain proper emission levels and prevent unnecessary energy consumption. These modern vessels are revolutionising harbour grids world-wide. That is not only due to the demand of a logistic infrastructure, but it is also due to high power and energy owing to OPS and battery-charging systems. They also require advanced communication systems to coordinate logistic systems digitally by employing the IoTs (Sadiq et al., 2021).

The OPS is an appropriate and effective solution to make ports and harbour free from GHG emissions, vibrations, and noise pollution (R. Winkel et al., 2016) (Fabio D'Agostino et al., 2021) (European Commission, 2021). The potential of emission reductions of employing OPS can be quantified, when the data of auxiliary engine power demand as well as duration of the vessels staying at berth is known (Stolz et al., 2021). OPS can be supplied mainly in three ways: local seaport microgrid in the islanded or isolated mode, local seaport microgrid in grid-connected mode, and independently by utility power grid supply. Indeed, seaport microgrid operating either in the islanded or grid-connected mode has a major advantage of employing RESs and energy storage systems (ESSs) locally, which does not only make sea ports self-sustainable but help reduce major emissions. Nonetheless, if OPS is supplied independently by the utility power grid, it also has an advantage of localising emissions from sea ports by generating power for OPS in remote areas. Therefore, this high-power demand for modern vessels requires an innovative way of designing and controlling harbour grids in such a way that they can fulfil the power and energy requirements of modern vessels, as introduced in Publications I and II.

2.2.3 Challenges and remedies for implementing OPS

Marine transportation has to deal with some typical challenges such as: reducing environmental pollution, increasing energy efficiency, integration of RESs, regulatory and legislative regulations, infrastructure complexity, power system stability, and growing power demand (Sadiq et al., 2021). Although OPS has been installed in a number of ports globally, its rapid spread across the world is still being impeded by several technical problems (Radwan et al., 2019). This mainly includes variations in voltage and frequency level between the shore and shipside and mismatch of power supply and demand of the vessels berthed at harbours.

The authors Radwan et al.(2019) determine the barriers that act as the greatest challenge to the implementation of OPS at the container terminals in Djibouti. Through analysis of the previously conducted research, the study identifies a number of barriers that must be overcome before the system can be put into operation. These barriers are further categorised as environmental, technical, economic, managerial, and regulatory issues (Radwan et al., 2019). As there are obvious advantages, it is necessary to make investments in the infrastructure of the ship as well as the port or terminal in order to promote OPS (Sciberras et al., 2015) (L. Wang et al., 2021).

According to the newly developed technical standards HVSC systems (IEC/ISO/IEEE, 2019), and low voltage shore connection (LVSC) systems (IEC/ISO/IEEE, 2014), the vessels can be retrofitted at a reduced cost. However, seaports require a significant retrofitting cost on investment for the appropriate electric infrastructure and an associated energy management system for OPS connections and to meet the on-board load requirement (L. Wang et al., 2021).

It is also important to note that in some areas, a tax is imposed on the purchase of energy from the shore, while in most cases, the purchase of electricity generated by auxiliary engines is exempted from such taxes (Spengler & Tovar, 2021). Taxation on OPS is also currently a topic of discussion across the EU. In this regard, the European Parliament has acknowledged the significance of the taxation scheme and issued a resolution requesting that its member states should investigate the differences in the taxation of energy (Spengler & Tovar, 2021). Sweden and Germany were already allowed by the EU to provide electricity at a reduced tax rate for OPS (Spengler & Tovar, 2021) (Ballini & Bozzo, 2015). The Publication II explored the current and future marine power and energy solution requirements of vessels as well as harbours. The authors of the Publication II are of the opinion that the main barriers in implementing are the lack of appropriate strict regulations, business models, taxation on OPS at some seaports, and etc. Moreover, some measurements should be taken to incentivise the seaports using environmentally friendly technologies. In this regard, the world-leading ports namely Antwerp, Rotterdam, Singapore, and Shanghai, encourage the use of OPS and have initiated a pricing policy of either giving incentives or charging penalty depending on the reduction or production of GHG emissions when staying at seaports (Sadiq et al., 2021). Therefore, it can be concluded that OPS can rapidly advance if all stakeholders, particularly ship owners, terminal operators, port administrators, researchers, policymakers, and local government take efforts together in making some suitable business models and promoting OPS as a solution to not only reduce emissions at seaports but also to make self-sustainable with energy-efficient solutions to support modern electric vessels.

2.2.4 Power and energy management of harbour area smart grid with smart control techniques

Current studies made by Ahamad et al.(2018), Kermani et al. (2022), Iris & Lam (2019), and Hein et al. (2021), suggest that increased electrification with the integration of RESs and ESS is a key solution for the environmental sustainability of future seaports. The seaports supporting OPS may require a large amount of power depending upon vessels to be berthed, and this may create new challenges for managing and operating seaports (Gennitsaris & Kanellos, 2019). This high load power demand leads to integrating more RESs and ESS to make seaport microgrid (Acciaro et al., 2014) (Kanellos et al., 2019) and smart ports (Lamberti et al., 2015), with suitable control strategies to maintain power balance and power quality. In order to manage and control the operation of multiple energy resources, the concepts of wise port by Parise et el. (2016) and HASG introduced in Publication I are developed. Smart ports exchanges electricity with seaports and electric or hybrid vessels, wise ports is supposed to trade electricity between seaports and utility grids, whereas, HASG copes with technical aspects such as the design and control of harbour grids with the application of BESS in such a way to deals with the requirements of modern vessels and seaports.

There are different control approaches applied in the literature to control, balance and manage power efficiently. The concept of combining a smart grid with OPS can provide various benefits. In contrast to a traditional smart grid, where loads are geographically distributed, the port is considered to have a concentrated huge load (J. Prousalidis et al., 2014). The study made by Sadiq et al. (2021) focuses on integrated power systems with multi-agent systems for implementing energy management systems in seaports. In this dissertation, novel harbour grid models are designed and developed, which combine OPS and battery-charging infrastructure for modern electric vessels into harbour grids.

Despite the numerous works that has been carried out to control and manage power for harbour grids, and no previous study has developed, tested and validated control algorithm for charging and discharging batteries to be implemented in harbour grids. Hence, in this dissertation, the Publication V integrates BESS in the Vaasa harbour grid and develops a simulation model of harbour-side BESC by applying real load profile data of OPS. The BESS is a feasible solution to cope with the growing power demands at harbour without extending the power supply infrastructure. It presents a practical approach in such a way that the charge and discharge of BESS is controlled depending upon peak load and off-peak load demands. The performance of harbour-side BESC is further tested with real-time setup of the SIL, and HIL tests by employing Generic Object-Oriented Substation Events (GOOSE) communication through the IEC61850 standards in Publication VI, and Publication VII respectively. Seaport microgrid should have flexibility for integrating intermittent RESs into seaport microgrid, where the application of BESS will be a viable option in modern seaports to balance the mismatch of power supply and load demand, shave peak load demand, and thus avoid extra capital cost on power system infrastructure.

2.2.5 Sizing and allocation of battery energy storage systems to support harbour girds

In order to cope with future energy needs, expansion of the power grid is often required. The expansion of the power grid is conventionally supported by constructing new lines, which indeed requires time, capital cost and efforts. However, instead of extending the capacity of the power grid, ESSs and especially BESS may be viable alternate solutions to not only strengthen the capacity of the power grid, but also meet the peak load demands (Aguado et al., 2017). The use of RESs for power distribution systems has adequately increased in recent years, which has a number of benefits, including energy sustainability, simplified maintenance, cost-effective energy sources, reliability and environmental friendliness. The BESS can be installed at medium as well as low-voltage levels for a wide range of applications, such as for integrating a high percentage of RESs into the grid. A business-oriented placement survey at every stage of BESS-based project is also essential for the overall successful placement of BESS in power systems having a high share of RESs. It makes these projects more lucrative, and decisively fast (Hameed et al., 2021).

The use of RESs in maritime microgrid greatly improves the energy efficiency and minimises the use of fossil fuels, which is a severe threat to environmental pollution. The ESSs play a significant role in the emergence of marine vessels' shipboard power system (Skjong et al., 2015). The appropriate size of the ESSs such as BESS, super capacitor and flywheel can be selected based on the load profile of the shipboard power system. This requires considering optimal power generation management and ageing effects of storage systems. The optimal size of the ESSs for shipboard power systems should be selected in such a way that a diesel generators operates very close to efficient loading conditions (Boveri et al., 2019). Based on the experimental method, the charging and discharging characteristics of BESS located in a real virtual power plant in Poland were determined by establishing the BESS model (Kaczorowska et al., 2020). Indeed, BESS should be designed optimally keeping a trade-off of power and energy characteristics. Because, in the case of BESS designed to supply power less than the power demand will result in the production of waste residual energy, whereas additional cost on investment and maintenance will occur if BESS was designed to supply more power than the power demand (Han et al., 2022).

The most commonly used battery types are Lithium-ion battery (LIB) (Roy et al., 2020) (Ovrum & Bergh, 2015), lead acid (Ahamad et al., 2018), and redox-flow (Hein, Xu, Wilson, et al., 2021). Redox-flow batteries having above 10,000 cyclic age can also be used for storage applications; however, they have low efficiency at high load demands, and danger of hazards owing to fluid electrolytes (Vicenzutti & Sulligoi, 2021), and lead-acid batteries have lower energy density and efficiency than LIB. Thus, in terms of grid-scale stationary ESS, LIB is supposed to remain the most popular technology because of its numerous advantages over other storage methods (Wali et al., 2022). The higher energy density characteristics make it a viable option to be integrated with RESs so that power supply continues when there is low power generation from RESs and the buying cost from the utility grid is high (Ahamad et al., 2018) (Darke, 2021). Batteries at seaports can be used to support OPS, shave peak load demands, and for swapping purposes (Ahamad et al., 2018) (John Prousalidis et al., 2019).

In Publication IV, research on the sizing and allocation of BESS has been conducted in the Åland Islands and it was found that the application of BESS in harbour grids can help avoid peak-load demand without expansion of the current capacity of any power grid as well support modern grids requiring a huge amount of power.

2.2.6 Optimisation techniques for operating harbour area smart grid

To reduce emissions, maximise the generation of power from RESs, increase energy efficiency, reduce power generation costs and earn incentives as a result of reducing emissions, some optimisation techniques are employed in the HASG. Sifakis et al. (2021) attempted to optimise hybrid RESs of Mediterranean ports in Crete according to the costs of tariffs and the rates of power and energy demand. The analysis included 17 alternate scenarios of seaport grid that were combined with multiple RESs in order to reduce the cost of electricity generation and emissions. In this analysis, they found that peak-shaving strategy yielded better results than cyclic charging because it eliminated the need of chargers requiring high-demand power by suitably re-sizing the system. The main purpose of energy management and scheduling of vessels at seaports is to maximise profit gain and reduce emissions at harbour areas. In this regard, the idea of optimising a coordinated scheduling method of grid-connected seaport micro-grids having uncertainties due to variable power production of RESs and load demand is proposed (Hein, Xu, Gary, et al., 2021). The proposed idea optimises a two-stage model with a conflicting nature of objectives based on day-ahead and hour-ahead planning to address unit commitment and uncertainties of RESs and load demand can maximise profit and reduce emissions at seaports. The optimisation technique applied by Taheri et al. (2021), identifies an appropriate operational schedule of a generator for a platform supply vessel that has four primary diesel generators for propulsion power and two auxiliary diesel generators for supplying power while staying at seaports. This paper asserts that the trip-ahead algorithm optimises the varying fuel consumption from diesel generators in such a way that minimises the cost of power generation and CO_2 emission profiles. The optimal dispatch scheme with a two-stage multi-objective optimisation problem is employed for hybrid vessels, which considers the cost of operation, emissions, and degradation of ESS (Hein et al., 2020). The first stage is day-ahead optimisation, which predicts intermittent data of PV for comparing the performance of objective functions, which is based on the second stage (hour-ahead) optimisation techniques.

The vessel operators can better understand basic optimisation and distinguish dispatch strategy varying with solar irradiation, ESS degradation and demand response. The relationship between allocating OPS and berth requires the development of a system for mutually optimising shore power and berth allocation in order to reduce costs and environmental degradation. Indeed, simultaneously reducing expenses and environmental degradation is challenging. Peng et al. (2021) presents a multi-objective cooperative optimisation model to achieve a balance between the two objectives and examines whether to allocate OPS to each berth based on a comparison of the economic and environmental benefits arriving ships. On the other hand, Roy et al. (2021) proposes that energy management optimisation comprises forecasting and planning across several hours. Nevertheless, due to uncertainties, microgrids need to be updated to be able to consider different decisions in real-time. Thus, it necessitates a real-time energy management system that utilises rule-based techniques and compares their results using the optimal strategy as described by Roy et.al. (2021). Developing energy management rules can help integrate power market dynamics into a techno-economical model.

Hence, it is concluded from the above discussion that optimisation techniques are employed by formulating problems of different domains and achieving multiple objective functions to reduce marine emissions and costs on electricity generation, increase energy efficiency and promote OPS by using RESs.

2.2.7 Digital solutions and internet of things for the development of harbour area smart grid

Conventional seaports that accommodate diesel-fuelled vessels are required to primarily cope with logistics services, whereas modern smart ports are required to meet modern port demand trends, such as electrification, OPS, digitalisation, and ESSs (Iris & Lam, 2019). These modern smart ports are multi-modal regional hubs of transportation that connect to airports, rivers, canals, rails, roads and other places that enable transport of goods. Digital technologies at smart ports solve problems such as port congestion and other problems that may evolve. Digital solutions can find, track, and combine the data that ports need to be environmental friendly and operationally efficient (Sadiq et al., 2021). Advanced digital technologies, including big data analytics and remote sensors, minimise the amount of operating costs, GHG emissions and frequency of system failures. They also improve information security, warehouse, and smart energy management. Digital technologies, such as IoT, enable smart ports to monitor logistics and fuel consumption, and it can also facilitate communicate between marine vessels and port terminals through digital data exchanges (Fruth & Teuteberg, 2017).

Currently, the Rotterdam port uses IoT for repairs and maintenance; the port of Hamburg has facility of 3D printing; Singaporean port employs cloud computing and big data; the port of Antwerp uses block chains; and the port of Los Angeles has digitalised information for all maritime sectors. At present, only 1% of port terminals across the world are fully automated, and only 2% are partially automated (Sciberras et al., 2016). Therefore, the number of smart ports need to increase by including enabling technologies such as the IoT, radio frequency identification, big data analysing tools, robots, cloud computing, and other technological solutions that allow ports to reduce environmental pollution and intelligently manage energy and logistics within seaports (Rajabi et al., 2019).

2.2.8 Business models for the development of harbour area smart grids

The marine industry is becoming crucial for the growth of the global economy, and 74% of European commodities are being transported through marine vessels (Sadiq et al., 2021). The development of seaport microgrids requires heavy investments due to the use of RESs, BESSs and other types of ESSs that come with a high price. On one hand, this development requires rapid actions, but, on other hand, it raises some questions that demand suitable business models for marine industries, such as: who should invest, and how investment cost should be shared among multiple marine stakeholders (Roy et al., 2020).

As an energy district, the seaport microgrid (Giuseppe Parise et al., 2016) enables the integration of RESs, expands grid storage capacity, and offers electricity to the market for sale through the main grid. Harbours are unique territories for developing economic models and energy plans (Lamberti et al., 2015). Examples of two practical seaport microgrids are in Hamburg (Germany) and Genoa (Italy), as discussed by Acciaro et al.(2014). The operational data demonstrates their efficacy (Fang et al., 2020). Uche-Soria & Rodríguez-Monroy (2019) have developed a waste management model based on circular economy in accordance with the EU policies for managing solid waste generated in the ports of the Canary Islands. Wang et al. (2021) suggest an innovative bi-level hybrid economic method to help the port administrative and the regulatory body to comprehensively boost the application of OPS. They propose that if upper-level regulatory bodies take the initiative and strategise an appropriate method to reduce the harmful environmental effects concerning berthing of ships at seaports. The port organisation on the lower level then selects and installs OPS by making the most financially advantageous and economically sound investment models. F. D'Agostino et al., 2021 provide a summary of Italy's OPS capacities that includes three important findings about the economic feasibility of OPS: ports should actively engage in the energy market, clearly mention the environmental impact, and generate a certain amount of seaport electricity from local energy solutions.

In order to encourage the use of OPS for short-sea shipping, a study by Martínez-López et al.(2021) provides a mathematical tool to evaluate certain environmental effects in ports. The rate of return of OPS on retrofitting cost in vessels is used to evaluate the impact of this charge on the economic performance of the vessel's operators. The allocation of OPS for each berth may not be a profitable because it balances economic gain and environmental protection; therefore, allocating OPS to berth to minimise costs and maximise environmental protection can be optimised (Peng et al., 2021). To cope with peak-load demand at seaports, some peak-shaving techniques such as lowering the peak load demand of shore-to-ship crane operations at container terminals (Geerlings et al., 2018), or battery charging and discharging operation at the Vaasa harbour grid, as proposed in Publication V, are also providing opportunities to develop business models to maximise benefits to the marine industry.

The following barriers exist for the development of business models to be applied when implementing OPS (Rob Winkel et al., 2015):

1. Who should invest for the development of OPS infrastructure? Which stakeholders, such as port owners, ship owners, power companies, local government or a combination of all stakeholders should invest?

2. There is a high amount of retrofit cost for ships to connect with OPS to meet with IMO requirements.

3. There are taxes on using electricity from the power grid in seaports in some places, but there are no taxes on electricity being generated by diesel generators operating on fossil fuels while they are docked.

4. Some ports may have OPS facilities, but their usage may be very limited, which is not good for a business model.

2.3 State-of-the-art and future marine solutions

A shipboard power system has evolved from the first shipboard electrical system design that has been in use since 1880, according to the new technologies and impetus by legislative and IMO (Skjong et al., 2015). Shipping technology is continuously evolving, especially concerning propulsion and power supply (Dale et al., 2015). The propulsion systems of marine ships has progressed from mechanical to electrical, and then to hybrid systems. Shipboard power systems has also likewise advanced from combustion to electrochemical, stored, and integrated power systems (Geertsma et al., 2017). The modern AES has an integrated power system that consists of RESs and ESSs. It has a power capacity of up to 100 MW to operate as an islanded microgrid (Jin et al., 2016). AES is considered as the most efficient replacement of the conventional mechanical system having electrical propulsion, and this concept is becoming standard for major shipyards manufacturers, especially for the largest ships in the world (Vicenzutti et al., 2015). The same standard may also be applied on ferries, shuttle tankers, and some other vessel types that are commonly used world-wide (Hansen & Wendt, 2015). The ESS employed in AES increases the operational efficiency and flexibility of the shipboard power systems as well as simultaneously reduce environmental degradation (Hein, Xu, Wilson, et al., 2021). These four objectives outline a sustainable transitions toward modern marine transportation systems (Pamucar et al., 2022):

1. Optimising operational performances of ferries

2. Converting conventional ferries to electric ferries

3. Converting conventional ferries to hybrid ferries

4. Buying new electric ferries

AES employs promising technologies and contributes to managing power intelligently by optimising power among various power generation sources. The other benefits of AES are the availability of integrating RESs, and fuel cells into the on-board power system of a ship. DC power distribution can eliminate the problem of synchronisation of all generators at a specified frequency (Nuchturee et al., 2020). Recent research that has been carried out has lead to the development of new technological systems with the application of efficient operating techniques in shipboard systems that aim to increase energy efficiency and decrease GHG emissions. The strategy of minimising fuel consumption at various operating conditions while meeting time-varying load demand has been proposed in research (Balsamo et al., 2020). Sun & Qiu (2022) highlight that the impact of AES on the voltage profiles in seaport microgrid on system-level has not been extensively investigated, and they suggest that a hierarchically coordinated voltage management method for AES and inverter-based RES can prevent quick voltage violations in seaport microgrid. Figure 2 shows the current state-of-art of on-board power systems, a paradigm shift from fossil fuels to bio-fuels and from non-renewables to renewables-based power generation.

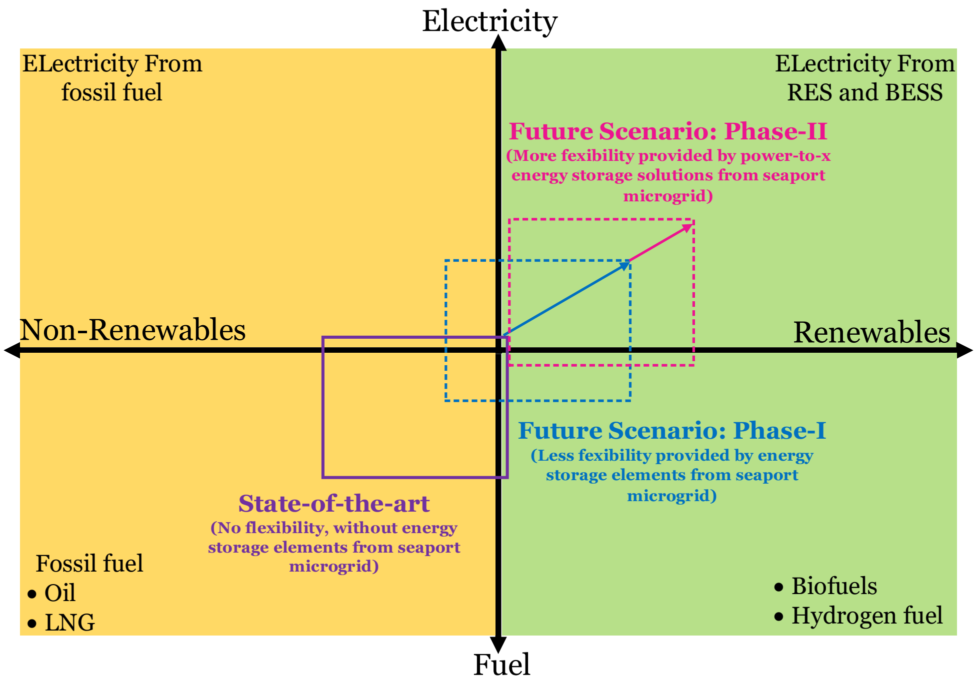


Figure 2. Present and future on-board power system of ships

At present, the majority of marine power generation is provided by non-renewable energy resources that lack the flexibility of power supply from a seaport microgrid. Future trends will likely include two phases: phase-I will include the development of hybrid power generation solutions (renewables as well as non-renewables) that have less flexibility of power supply from seaport micro-grids, and phase-II will include all power solutions from RESs that have more flexibility of power supply from seaport micro-grids with advanced solutions for power-to-x ESSs. This major shift occurs mainly due to strict emission reduction regulations and targets set by IMO (IMO, 2021), and EU-Directive 2005/33/EC (Directive 2005/33/EC Of the European Parliament and of the Council, 2005). Besides these emission regulations and targets, continuous development in technologies enables new smart and sustainable energy solutions, which can significantly decrease emissions, increase energy efficiency, reduce fossil-fuel usage and increase e.g. lifespan of ship engines. Future modern smaller ships may operate fully on BESS, whereas large ships gradually move towards more hybrid solutions based on biofuel or LNG along with RESs and ESSs.

2.4 Summary of the chapter

The air pollution and toxic emissions emitted by conventional vessels employing fossil fuels, especially at harbours, cause many issues including adverse effects on health of the inhabitants. This is raising the global awareness and this is why many well-known international, European, and local organisations pursue strategies to lessen emissions, conserve fuel and improve the energy efficiency of marine transport. The rules and initiatives put forward by said organisations that seek to regulate hazardous emissions have stimulated technical advancement, and they are transforming the paradigm to favour non-conventional fossil-fuel vessels, such as modern electric and hybrid ships. These contemporary vessels will finally shift trends from conventional seaport grids towards smart ports, wise ports and HASG with RESs and sustainable solutions for vessels and harbour grids. Therefore, research primarily advances towards the design and control of harbour grids focusing. The main research objectives include reducing emissions, increasing energy efficiency and making some suitable business models for modern vessels facilitating them with OPS and battery-charging infrastructure. This chapter provides an extensive analysis of the existing and foreseeable maritime solutions along with defining the main characteristics, problems, obstacles and challenges of implementing OPS.

Even though using OPS has many benefits, only a few ports really benefit from it partly due to a lack of acceptable business models and severe regulations. If all the stakeholders, including ship owners, terminal operators, port administrators, researchers, regulators and local governments, participate concurrently in developing appropriate business models for promoting it, OPS technology can advance quickly. The concept of HASG introduced in this dissertation by connecting the utility grid along with RESs and BESS can better control and manage the additional power requirements of the modern vessels due to OPS and battery-charging loads. In the future, more research and development is required for implementing novel methodologies and technologies for smart power and energy management incorporating control and communications, multiple types of ESSs including BESS, digitalisation, big data analysis and the IoTs in HASG. Finally, it is concluded that there are still some barriers in implementing business models for OPS, and international organisations, along with local policy makers, are striving to develop appropriate solutions.

3 TECHNICAL DESIGN ASPECTS OF HARBOUR AREA SMART GRIDS

This chapter is based on Publication I and Publication II. It starts with presenting a quick review of the existing standard for HVSC systems (IEC/ISO/IEEE, 2019), based on which harbour grid models are designed in Publication I and II. This chapter summarises one of the main contributions of this dissertation by introducing the novel concept of HASG and it also discusses the technical design aspects of several HASG models, which indeed serve the main objectives to support the OPS and battery-charging requirements of modern electric and hybrid vessels. Also, some results from simulations are presented from Publication I based on one HASG model, which can support hybrid and electric vessels with OPS and battery-charging configurations. This chapter addresses the following research question:

RQ1: What are technical design aspects, standards, and barriers in designing HASG supporting OPS and battery charging infrastructure?

3.1 Standard for high voltage shore connection systems

Many technical problems with OPS have been resolved due to the current standard for HVSC systems (IEC/ISO/IEEE, 2019), particularly the HVSC voltage levels (6.6 kV or 11 kV). This standard summarises the maximum permissible voltage deviations under steady state and transient conditions, exposes potential power quality problems and specifies the typical maximum levels of total harmonic distortion. In addition, the HVSC standard provides detailed explanations about numerous other electrical characteristics, including power protection and human safety considerations. This standard covers the level of shore and ship short-circuit current contribution; equipotential bonding established between the shore earthing electrode and the ship's hull; the neutral earthing resistor’s value for the shore-side transformer, sockets, plugs and switchboards; the maximum limits of power capacity for each cable; and the minimum shore-side power capacity that can be assigned to each vessel. The requirements for static or rotary frequency converters for the OPS connection are also described in the HVSC standard. The standard highlights the ship's requirements for complying with power system monitoring, control, safety, protection and other general issues concerning OPS. Please see Figure 3 for the HVSC schematic diagram that primarily includes OPS and the ship's networks. The protective relays, circuit breakers, control cables and communication cables are situated between these two networks’ onshore and on-board power systems. In addition, for the same power to be transformed from onshore to on-board the vessels, a shore-side transformer is used to convert high voltage power supplies to low voltage power supplies. as well as provide galvanic isolation to the connected ship from other connected ships or consumers.

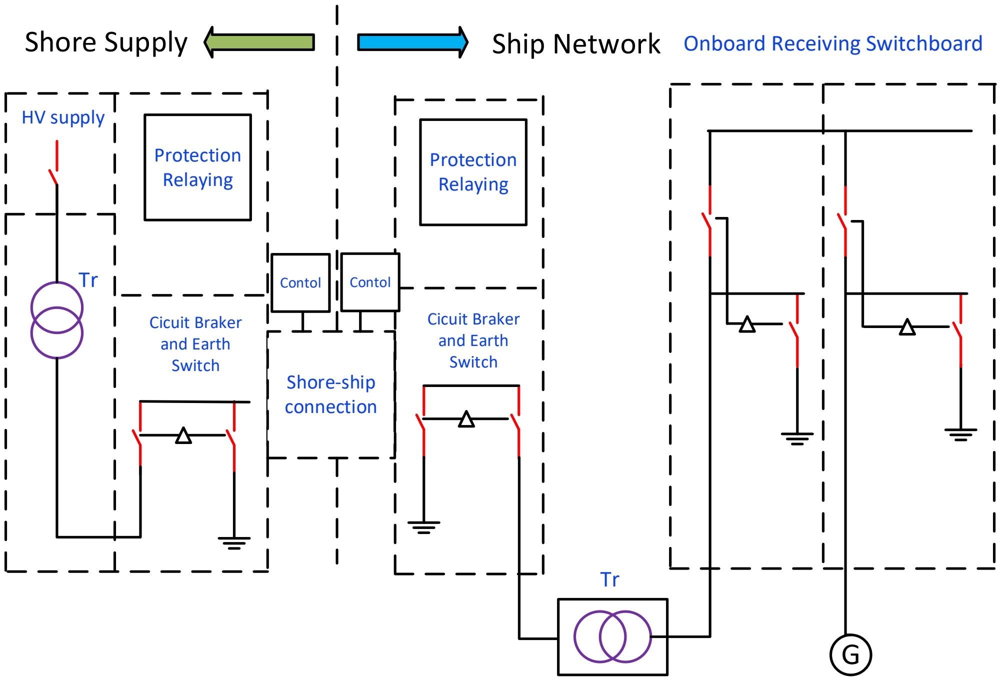


Figure 3. Schematic diagram of HVSC systems (IEC/ISO/IEEE, 2019)

3.2 Harbour area smart grid

The seaport power system must adopt cutting-edge and creative strategies to reduce energy usage, including local energy production, ESSs, automated guided vehicles and cranes, and improved reefers (G. Parise et al., 2016). When considering the significant potential of local power generation from RESs, variable loads such as electric vehicles, battery-charging stations, and refrigerated containers (Kanellos et al., 2019) (Kanellos, 2017), the concept of a smart grid for ports can be a viable alternative. In order to achieve the objectives of reducing peak-power demand and energy efficiency, the aforementioned loads can be flexibly managed by shifting peak-demand time (Kanellos, 2017). To optimise load demand and power management, some appropriate techniques, such as multi-agent systems (Kanellos et al., 2019) and pattern recognition (Gialketsi et al., 2012), can be applied. By using an ESS that can be charged at low energy demand, OPS to ships can be transformed into smart loads (J. M. Prousalidis et al., 2011).

Lamberti et al. (2015) presented an idea of a smart port that allows for the exchange of electricity between modern electric or hybrid ships and port; however, it requires a functioning harbour grid infrastructure. By utilising the concept of wise port introduced by Parise et al. (2016), the electricity at the port can be economically traded between seaports and the utility grids. The notion of wise port reveals the inevitability of a microgrid at seaport and assumes the harbour area as a particular region that should focus on the management of electricity from the perspective of developing business models. The authors Prousalidis et al.(2014), and Prousalidis et al.(2011) suggested to combine the smart grid with the OPS to gain a number of benefits. In contrast to a normal smart grid where minor loads are geographically distributed, the seaport consists of a concentrated huge load.

A review of literature revealed that little attention was paid to design, model and validation of the performance of the harbour grid to support modern electric and hybrid vessels. Therefore, a novel concept of HASG has been introduced in Publication I, which supports OPS to the docked vessels at seaports. Up to the best knowledge and literature review made, it was first time to design and model HASG with integration of RESs and BESS along with utility grid to support OPS, battery-charging load for electric and hybrid vessels, and other harbour loads. The performance of the HASG has also been validated in the steady state as well as transient state, so it complies with current HVSC system standards (IEC/ISO/IEEE, 2019). Figure 4 depicts a single-line diagram of the HASG, where 20 kV Harbour Area Bus is the common coupling bus, which is fed by the main grid, the HASG and the WT near the harbour area. To ensure the reliability and stability of the entire power system, the HASG comprises the PV and the BESS at different places. The Hybrid Vessel Bus and frequency converter stations are situated in close proximity to the vessel terminal at the harbour. When OPS connected with vessels, the frequency converter converts 20 kV, 50 Hz to 20 kV, 60 Hz in order to supply power to vessels working at 60 Hz. There are two shore-side transformers that are linked to the hybrid bus and frequency converter station in order to reduce the voltage from 20 kV to 6.6 kV at 50 Hz and 60 Hz, respectively. The HVSC standard requires a shore-side transformer to galvanically isolate one ship from another ship or another power consumer. Conversely, if a separate transformer for OPS is available on-board, this may not be required at the harbour grid. Therefore, two separate ship buses or a double bus bar are necessary to supply 50 Hz and 60 Hz power to the ships. The harbour-side BESS is connected with a Hybrid Vessel Bus, 20 kV, 50 Hz with bi-directional converter for converting alternating current (AC) to direct current (DC) and vice versa to charge and discharge the BESS. The single-line diagram shows the proposed HASG model developed in PSCAD software, which provides OPS to ships and supports charging of electric and hybrid ships' batteries in containers. In the proposed HASG model, each battery within a container has a capacity of 2 MWh, a charging rate of 0.1 C, and is interchangeable with the discharged batteries of electric and hybrid vessels during their staying time at harbours.

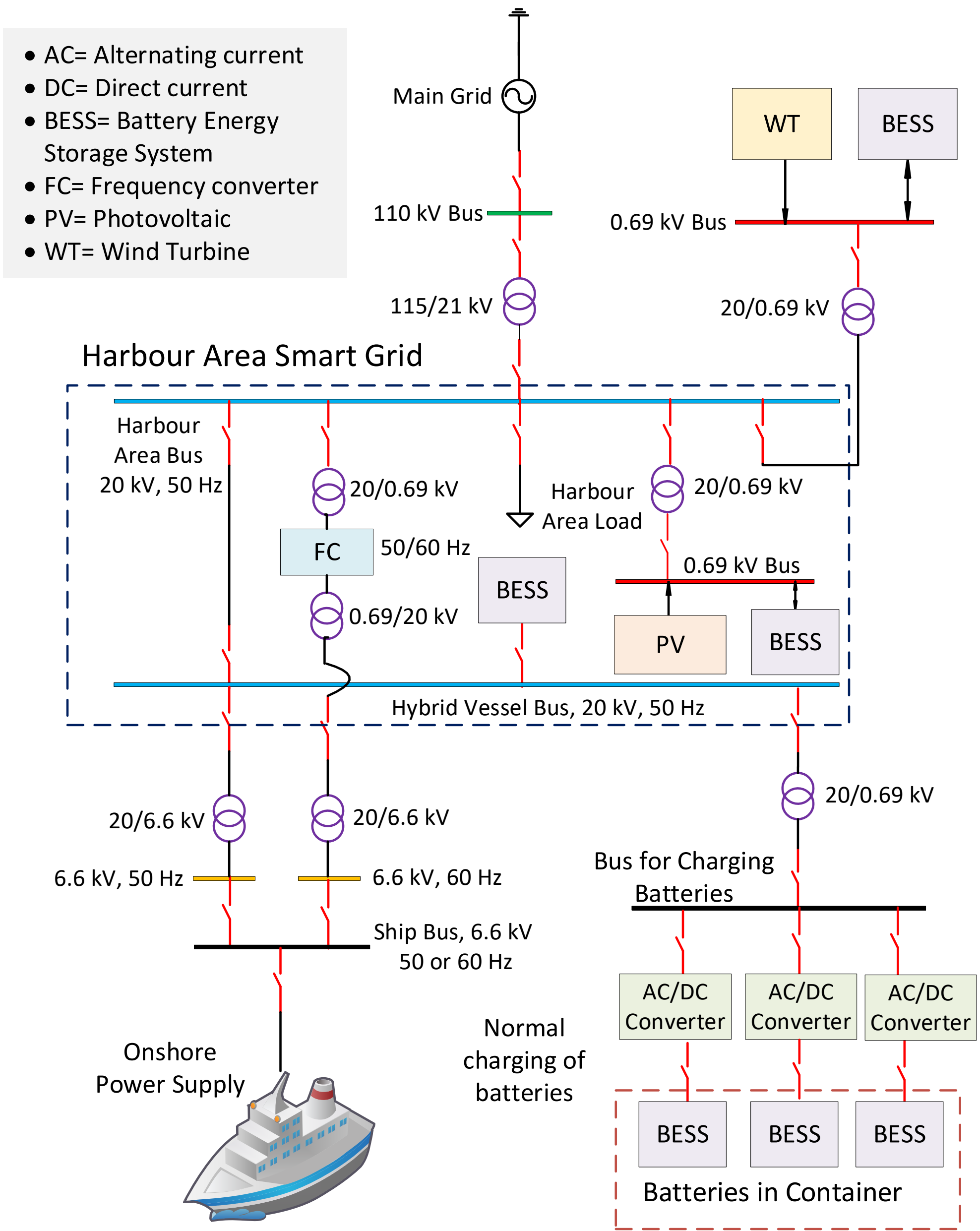


Figure 4. Single -line diagram of the Harbour Area Smart Grid (Publication I)

The integration of WT and PV into the harbour grid can primarily generate emission-free electricity from renewable and sustainable energy sources. When compared to central power plants, distributed generation (DG), by RESs, has a relatively cheap operating cost and can reduce power losses of utility supply. To avoid the expansion of the current capacity of any power grid, the DG units can be situated close to the main harbour load. As the output power of RESs is unpredictable (Carrasco et al., 2006), it can raise concerns about the reliability of harbour grid operations (J. M. Prousalidis et al., 2011). In order to achieve optimum benefits from volatile RESs, particularly in islanded mode, the integration of ESSs (Sørensen et al., 2017) is a viable alternative for enhancing the HASG's reliability and stability (J. M. Prousalidis et al., 2011). The BESS as a form of ESS will play an important role in marine applications due to the decrease in BESS cost (Roy et al., 2020), improvement in reliable operation and performance of BESS (Jin et al., 2016) (Divya & Østergaard, 2009). Figure 4 shows the HASG designed in Publication I, which is connected with PV, WT, BESS and the main grid power supply. In this HASG configuration, the exchange of power with the main grid should be coordinated among all power sources. The BESS is technically suited for auxiliary service applications, such as black start, voltage support, and frequency regulation (Palizban & Kauhaniemi, 2016).

In the grid-connected mode of operation of the HASG, the harbour-side BESS can smooth out the power fluctuations of RESs in the HASG and support the weak grid to balance the power and improve power system stability and reliability. In the islanded mode of operation, the load shedding may not be a realistic option due to the crucial schedule of the vessel staying at the harbour. Thus, the harbour-side BESS, as a master unit, should control the HASG power balance to ensure uninterrupted power supply to ships in the islanded mode of operation of the HASG.

Compared to the model presented in Publication I, the design of HASG can be implemented with numerous variations; nonetheless, Publication II has developed two modified variants that are both technically and economically viable. The following subsections provide a description of these models, their major properties and a technical examination of all harbour grid configurations. This section focuses mostly on the potential configurations of designing HASG and its viability, which depends on a variety of criteria such as space at the port, the type of vessel, the duration of its stay at a port, availability of infrastructure, and the port's power and energy needs.

The next sections provide an explanation of these models, their main features and a technical examination of all harbour grid configurations. There are many factors that affect the possibility of designing alternative HASG configurations, including: the space at a seaport, availability of infrastructure, the type of vessel, length of time staying at a seaport, and the power and energy demand of the seaport.

3.2.1 Modified version 1 of harbour area smart grid

Figure 5 depicts the modified version 1 of HASG, which includes the following alterations in comparisons with the schematic diagram shown in Figure 4.

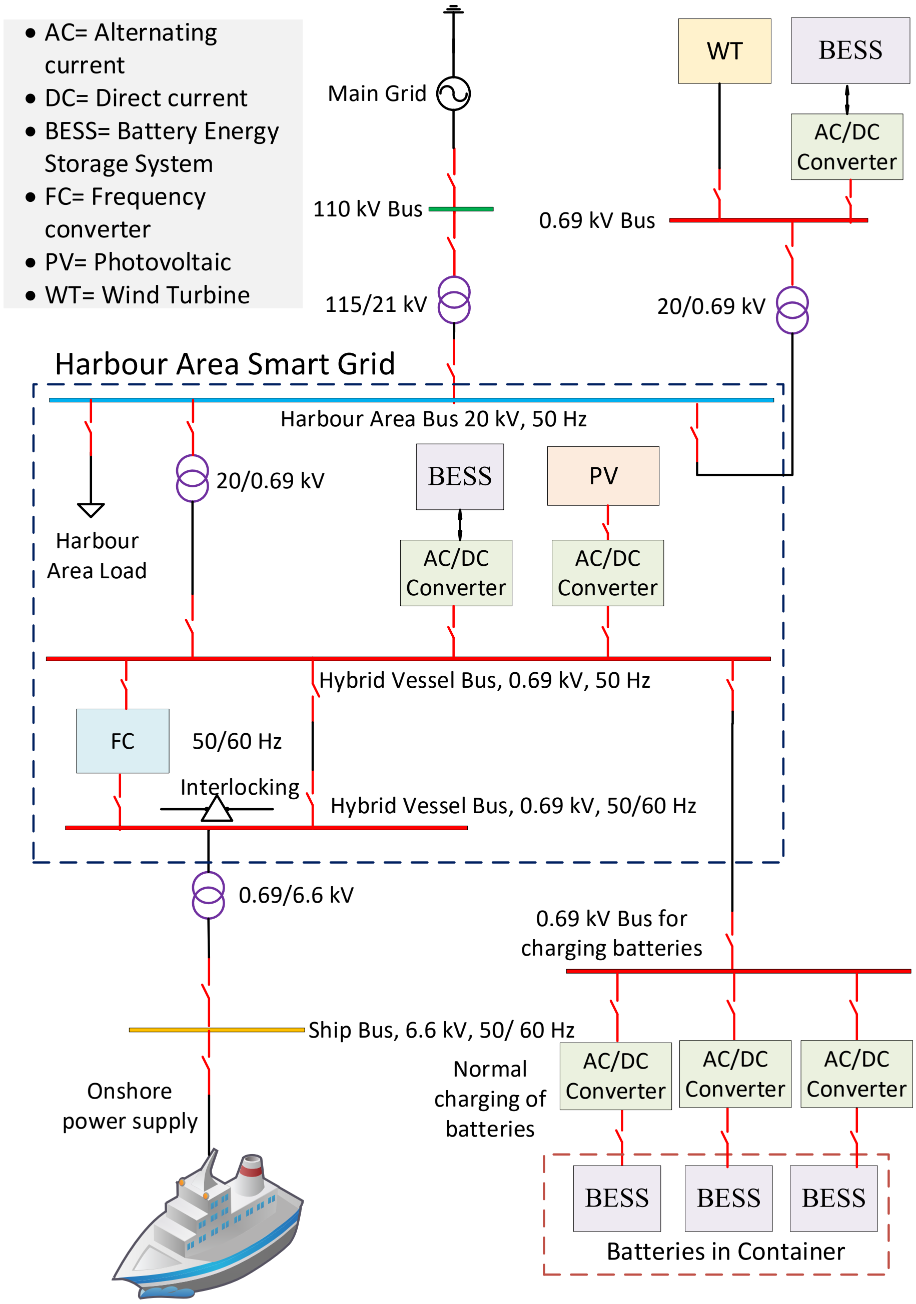


Figure 5. Modified version 1 of the Harbour Area Smart Grid (Publication II)

The major concept is to build the hybrid bus with 0.69 kV rather than 20 kV by employing a single transformer for both 50 Hz as well as 60 Hz vessels. However, this single transformer must be designed for 50 Hz to supply power both vessels operating on 50 and 60 Hz; otherwise, the windings of the transformer would be damaged by the drop in reactance and rise in current, if operating on a 50 Hz power supply when designed for a 60 Hz supply. For safety and protection, the interlocking switch is employed such that either the 50 or 60 Hz vessel is energised at the same time. In comparison with the HASG in Figure 4, this configuration saves four transformers: one for charging the batteries, another for connecting the PV and BESS in the HASG to the Harbour Area Bus, 20 kV, and two more for connecting the frequency converter between the Harbour Area Bus, 20 kV and the Hybrid Vessel Bus 0.69 kV. Thus, as compared to the design in Figure 4, this modified version 1 of HASG reduces the quantity of transformers and their related protection equipment by half, which entails lowering the total expenses of the HASG as well as the space needed on seaports.

3.2.2 Modified version-2 of harbour area smart grid

Further modifications in the HASG design model in relation to the schematic diagram of Figure 5 are done in schematic diagram of modified version 2 of HASG, as shown in Figure 6. The key modification in the design model between Figures 5 and 6 is the substitution of the frequency converter with the BESS supply. In this modified version, the BESS is situated in a difference place, and it will dedicatedly supply power for the 60 Hz vessels. That eliminates the need for a frequency converter. Replacing a capacitor of the frequency converter with BESS downscales the power rating and power supply for the AC/DC converter for charging batteries as well as peak-power ratings of the grid components that supply power to the converter. Finally, this configuration could lower the entire cost of the system, and it is especially ideal for harbours with a weak grid system. This is because it allows to reduce the peak power demand from the grid by charging the BESS at lower rate of 0.1 C, while the OPS load may be supplied from the BESS at the required (higher) power demand of the vessel. This design has the additional feature of changing energy demand by charging the BESS during off-peak hours and supplying energy to harbour grids when needed. Furthermore, this technique would be more appropriate for 60 Hz vessels that do not require a substantial amount of energy for OPS and whose calls to 50 Hz seaports are for short duration and infrequent. As a result of the reduced number of components, this design requires less harbour space than other options. The BESS in this design must have a power capacity higher than power needed for 60 Hz vessels. This is an innovative approach, and it has the potential to be implemented for harbour grids supplying OPS to the vessels requiring power supply at different frequency than the grid supply frequency. According to current research findings and literature review it is concluded that this is a novel system design and it can be useful when applying OPS to vessels, which are operating at mismatched frequencies between vessel and grid power supply; thus, it has the potential to be implemented for harbour grids.

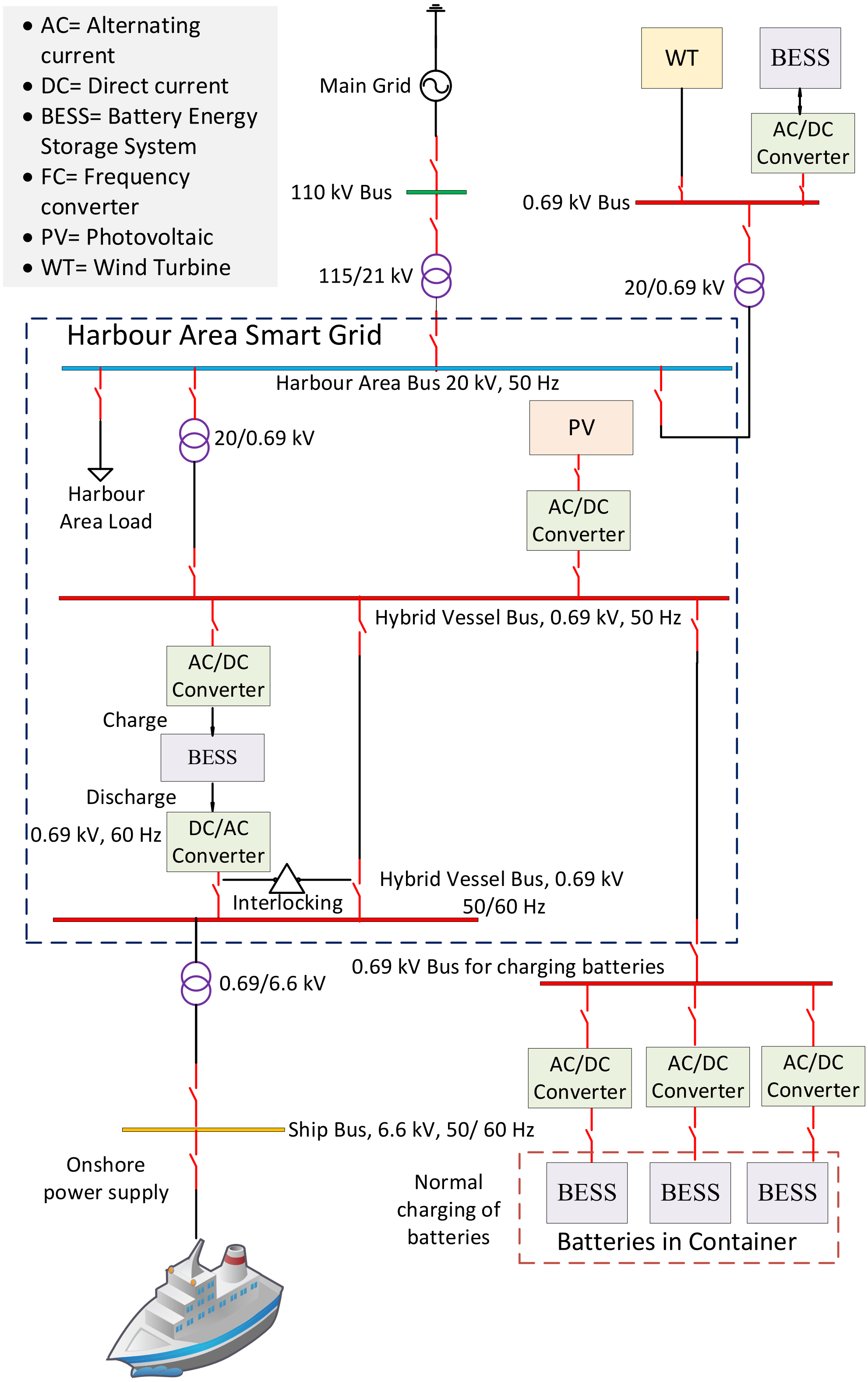


Figure 6. Modified version 2 of the Harbour Area Smart Grid (Publication II)

3.3 Simulation results

The HASG model in Publication I is developed using the PSCAD software. Publication I's main findings validate that the designed HASG supports OPS and battery-charging systems and performs well in both steady and transient states. The grid component data, as described in Section 3.2, was used in the simulation model in such a way that the simulation model is assumed to be as close as possible to the behaviour of a real system.

Table 2 shows the results of steady-state operation, where the voltage and frequency levels at all buses are also within specified limits of HVSC standard requirements (voltage limits are +6% and −3.5% of nominal voltage, and frequency limits are ±5% of nominal frequency). The active and reactive power flows at different buses are taken positive for power consumption elements and negative for power generation elements in the HASG model.

The HASG model is also simulated to observe the performance during the transient mode of operation. Figure 7 illustrates the dynamic behaviour of voltages in the harbour area and hybrid vessel buses. The 3-phase-ground fault was applied at the time, t=5 seconds for duration of 0.2 seconds at the bus connecting WT. The voltage at the harbour area bus and hybrid bus drop during fault duration, but this voltage drop is within 10% of the rated voltage. Moreover, the control action from the WT recovers the operating voltage quickly to the pre-fault voltage levels. Thus, the simulation results from the Publication I validate the designed concept of the HASG.

Table 2. Steady state simulation results of power flow (Publication I)

System Components	Voltage (kV)	Frequency (HZ)	Net P (MW)	Net Q (MVAr)
Main grid bus	110	50	−2.301	−0.160
WT	0.736	50	−2.734	−1.003
PV	0.710	50	−0.943	−0.262
BESS	0.707	50	−1.974	0
Harbour area load	20.392	50	1.559	0.316
Battery-charging load	20.265	50	1.848	0.370
Ship Load 1	6.582	50	2.386	0.447
Ship Load 2	6.616	60.004	2.007	0

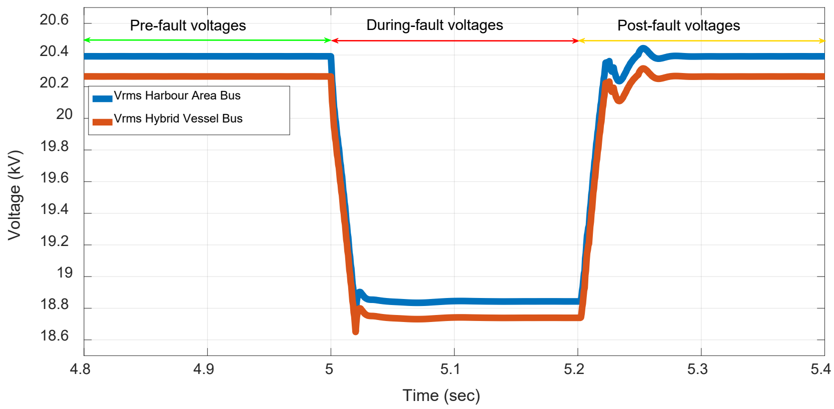


Figure 7. Simulation results of voltages in harbour area and hybrid buses during 3-phase fault applied on WT (Publication I)

3.4 Summary of the chapter

OPS offers an appropriate solution for reducing emissions and making a healthy environment at harbours. Chapter 3 presents one of the main contributions of the dissertation by designing and modelling HASG, which can support modern electric and hybrid vessels for OPS as well as charging batteries for vessels. There are several HASG models developed and simulated in the PSCAD software. The results obtained are satisfactory and adhered to current standard requirements, such as voltage limits at the bus bars. While there could be other reasons to design a HASG, the main focus was to develop novel designs and models that could meet certain technical constraints. One of the proposed HASG could be a revolutionary step in the field of OPS, where the DC bus capacitor of the frequency converter is supposed to be replaced with BESS enabling OPS with mismatched frequency levels of on-board and onshore power systems while simultaneously providing peaks shaving and other ancillary services. The key features of the proposed design models for the HASG are to support the vessels for OPS, provide a facility for charging the batteries, and employ the RESs and BESS at harbours. Each designed model proposed in this chapter may be appropriate for a specific case depending on the technical specifications of the ships, the available space and the infrastructure at seaports. As the modern electric and hybrid vessels are revolutionising the harbour grids, this research asserts that a paradigm shift will soon modernise harbour grids to the concept of HASG by integrating RESs along with utility grid power supply, incorporating multiple types of ESSs, including BESS, to facilitate new electric and hybrid vessels. In the future, the application of BESS for compensating peak-load demand, especially with weak utility grid connexions, will play a crucial role in designing HASG. Moreover, digital and IoTs will help foster power and energy management as well as logistic and other necessary operations of harbour.

4 DESIGN OF HARBOUR GRID MODELS WITH VARIOUS BATTERY-CHARGING STATION CONFIGURATIONS

This chapter discusses the need for battery-charging infrastructure for electric and hybrid vessels in harbour grids. This chapter is based on Publication III and covers one of the main contributions of the dissertation by developing various novel HASG configurations that support OPS and battery-charging configurations for modern vessels. Alternate battery-charging configurations along with technical aspects of implementation is also compared. The two HASG configurations were developed and simulated in the PSCAD software. They are termed as slow- and fast-charging configurations of HASG, and the detailed simulation results are presented in Publication III. This chapter addresses the following research question:

RQ2: What could be the different types of battery-charging configurations of HASG and how to compare them based on specific vessel and harbour grid requirements?

4.1 Battery-charging stations in harbour area smart grids

A historical overview of shipboard power systems (Skjong et al., 2015) shows that the advent of solid-state power electronics technology steered in an era that ultimately resulted in the creation of AESs in the marine industry. Shipboard power systems have eventually evolved from thermal to electrochemical and from electrochemical to stored and hybrid power systems (Geertsma et al., 2017). BESS in the hybrid power system of vessels can shave peak load demand, improve energy efficiency, dynamic performance and spinning reserve (Sørensen et al., 2017) (Mutarraf et al., 2018). BESS used in marine applications should have a high-energy density, a long discharge time, and a flat voltage-drop curve versus time (Dedes et al., 2012). Due to its well-established technology, high efficiency, high power and high-energy density, the LIB can be used in electric vehicles (Panday & Bansal, 2016) as well as in a variety of ships (Jin et al., 2016). In addition, smart charging systems of BESS can make use of flexible charging patterns with an increased amount of the penetration of RESs (Yanhui et al., 2013).

Hybrid vessels reduce emissions as well as fuel consumption by 10–35% using advanced control techniques (Geertsma et al., 2017), and those vessels also optimise the operation of shipboard power systems by employing BESS (Misyris et al., 2017). A comparison of energy efficiency among AC, DC, and inductive shore-to-ship charging solutions for propulsion of short-distanced ferries has been indicated by research (Karimi et al., 2020a). Initially, a swappable battery method was used to decrease the battery-charging time, but this method increases the cost and raises safety concerns because of the risks of involving manpower. The development in the field of fast charging of batteries has now minimised charging time, and it can now possibly replace the swapping method of the battery (Karimi et al., 2020b). Analysis of battery-powered ferries currently in operation shows that the installed BESS capacity varies between 500 kWh and 5000 kWh, and it requires charging power of up to 10 MW. Fully electric ferries are small in size and limited capacity imposed by the weight and the size of the BESS are suitable for maintaining shorter routes where the focus is mainly on passenger transport (Cuculić et al., 2022).

A paradigm shift in the maritime industry towards modern battery-powered electric vessels or hybrid ships integrated with BESS has occurred due to strict regulations regarding emission (Geertsma et al., 2017). However, designing the HASG that supports battery-charging infrastructure either off-board or on-board vessels in addition to OPS is a challenging task. The key challenge when designing battery-charging infrastructure for seaports is to ensure that the charging stations are able to cope with the demanding schedules of ships, which often need to be charged at very short notice, as described in Publication III. In order to frequently charge the batteries, these contemporary vessels will need battery-charging stations in ports. As a result, in addition to OPS, the harbour area grids should be designed to accommodate battery-charging configurations for hybrid and electric vessels, as highlighted by Publication I and II. Therefore, Publication III addresses the infrastructure to charge the on-board BESS for contemporary battery-powered vessels from a technological standpoint.

After a careful review of the relevant research made by the authors Sørensen et al. (2017), Misyris et al. (2017), Alnes et al. (2017), Sciberras et al. (2017), and Skjong et al. (2017), it is deduced that a comprehensive analysis of charging methods and alternative charging configurations has not been provided. The concept of the HASG is already been presented in Publication I, but Publication III explores multiple configurations of battery-charging for vessels in addition to supplying onshore power. Thus, the following research questions are raised:

- What could be different types of battery-charging configurations for HASG to support electric and hybrid vessels?

- What are the key characteristics and technical challenges of different types of battery-charging configurations of HASG?

• How can these various battery-charging configurations of HASG be implemented in practice?

The main objective of Publication III is to address the above research questions in detail by presenting HASG configurations that facilitate various battery-charging scenarios along with OPS. This study investigates slow and fast charging options and draws input based on talks with marine industry experts. The outcomes of the PSCAD simulations are presented in Publication III, and some of those simulation results are shown in this chapter, which demonstrate that the performance of these models is adequate and they could be implemented in practice.

4.2 Battery-charging methodology and configurations supporting onshore and on-board vessels

The various charging methods and algorithms that depend primarily on the type of battery and its chemistry have been developed, and their goals seek to reduce the charging time, improve efficiency and extend battery lifespan. Single and multi-rate constant-current, constant current/constant voltage (CC/CV), fuzzy logic control, double-loop control, pulse charge, and boost charge are examples of these techniques (Vo et al., 2012). The CC/CV charging is the most recommended and prevalent technique for both lead-acid and LIBs (Vo et al., 2012) (Dearborn, 2005). The four steps of the charging method are comprised of this sequence: trickle charge, constant current, constant voltage, and charge termination (Dearborn, 2005). Trickle charge is employed to restore deeply discharged batteries until they reach the specified threshold voltage (80% of nominal voltage). Depending on whether slow or rapid charging is necessary, the batteries are charged with a constant current of 0.1–1 C (10–100% of rated current) following trickle charge. The battery voltage and charger voltage with a constant-current charging increase gradually until the maximum voltage of 115% is reached. When LIBs are being charged with a constant current, a current higher than 1 C should be avoided because it does not speed up the charging process, but it causes an overvoltage (Dearborn, 2005). When the voltage reaches 90%–95% state-of-charge (SOC), the charging rate is either slowed down to 0.02–0.07 C or stopped completely. Lead-acid batteries are put on a trickle charge until the charge finishes. The LIBs should not be kept on trickle charge until the charge is finished because it would cause plating of metallic lithium, which can cause the battery to explode (Dearborn, 2005).

In this study, a constant current of 0.1 C for 10 hours of slow charging of batteries and a constant current of 0.5 C for 2 hours of fast charging of batteries are provided to the battery-charger models developed in PSCAD software. A set of three 2 MWh BESSs are charged to a voltage of 0.69 kV at the above C rates with a constant current of 290 A for off-board slow charging and 1450 A for on-board fast charging, which complies with the LVSC standard for ports (IEC/ISO/IEEE, 2014). The battery-charger models can deliver the necessary DC voltage and current for charging batteries at any certain initial SOC, regardless of whether they choose fast or slow charging techniques. In addition, the SOC is normally predicted using model-based estimators (Wei et al., 2016), but Publication III takes into account the terminal voltage. A nominal voltage of 2 MWh BESS is 0.6 kV, and at 100% SOC, the BESS can achieve a maximum voltage of 0.69 kV. Despite the fact that the CC/CV strategy is suggested for batteries, this model only simulates the constant-current stage (leading to a specific SOC) due to the short simulation/computation time preferred in the PSCAD software. As this research implements the recommended charging rates of value less than 1 C, it is assumed that there would not be any temperature rise or overvoltage. Thus, the battery life cycle would not be affected in these case studies of slow- and fast-charging configurations. To control the charging current, a three-phase AC–DC converter, a DC-link and a high-frequency transformer isolated DC–DC converter were used to model the chargers in PSCAD software.

In comparison with the HASG presented in Publication I, the configurations in Publication III have been modified by considering the realistic dimensions of harbour components, such as ratings of transformers, the size and length of cables, and various other equipment. The main grid bus of 20 kV, 50 Hz fed by the main grid through transformer T1 of the rating 20 MVA, 115/21 kV is located at a distance of 5 km from HASG and supplies to Harbour area bus of 20 kV, 50 Hz. The WT power, along with BESS located at 10 km distance from HASG, also supplies to same Harbour area bus of 20 kV, 50 Hz through a step-up transformer T2 of the rating 3 MVA, 0.69/20 kV. The PV power, along with BESS located at 5 km distance from HASG, also supplies to the same Harbour area bus of 20 kV, 50 Hz through a step-up transformer T3 of the rating 1 MVA, 0.69/20 kV. The Harbour area bus of 20 kV, 50 Hz further supplies power to the Harbour area load, and Harbour area bus of 0.69 kV, 50 Hz through step-down transformer T4 of the rating 10 MVA, 20/0.69 kV. The dedicated harbour-side BESS of the rating 1 MVA, 0.69 kV connected with the Harbour area bus of 0.69 kV, 50 Hz keeps discharging power to the HASG when peak-load demands of the HASG exceeds the power supply from the main grid and keeps charging BESS when the power supply from the main grid exceeds the power demands of the HASG. The frequency converter is connected between Harbour area bus of 0.69 kV, 50 Hz and Port bus of 0.69 kV, 60 Hz for OPS to the vessels requiring 60 Hz power supply. Thus, the HASG consists of three main buses, namely Harbour area bus of 20 V, 50 Hz, Harbour area bus of 0.69 kV, 50 Hz and Port bus of 0.69 kV, 60 Hz. Only in configuration D, port bus of 0.69 kV, 60 Hz is not employed, and the OPS is directly connected with Harbour area bus of 0.69 kV and 50 Hz. The frequency converter is connected with Onshore bus 6.6 kV. The distance from HASG buses to Onshore bus 6.6 kV is kept 2.5 km, and the distance from Onshore bus 6.6 kV to Onboard bus 6.6 kV is considered as 0.2 km.

In addition to the provision of an OPS, this research has evaluated several HASG configurations with battery-charging systems either onshore or on-board; thus, the particulars of the main power supply for the harbour and the HASG are not presented here. Nonetheless, onshore and aboard power systems and some of the most significant technological issues are described and compared in depth. Furthermore, these several battery-charging configurations comply with the technical standard requirements (IEC/ISO/IEEE, 2019) (IEC/ISO/IEEE, 2014).

Figure 8 classifies all the configurations into the three main charging configurations: on-shore (slow charging), on-board (fast charging), and a hybrid (slow- and fast-charging). They are further subdivided into five configurations (A, B, C, D and E). Further details are given in Publication III.

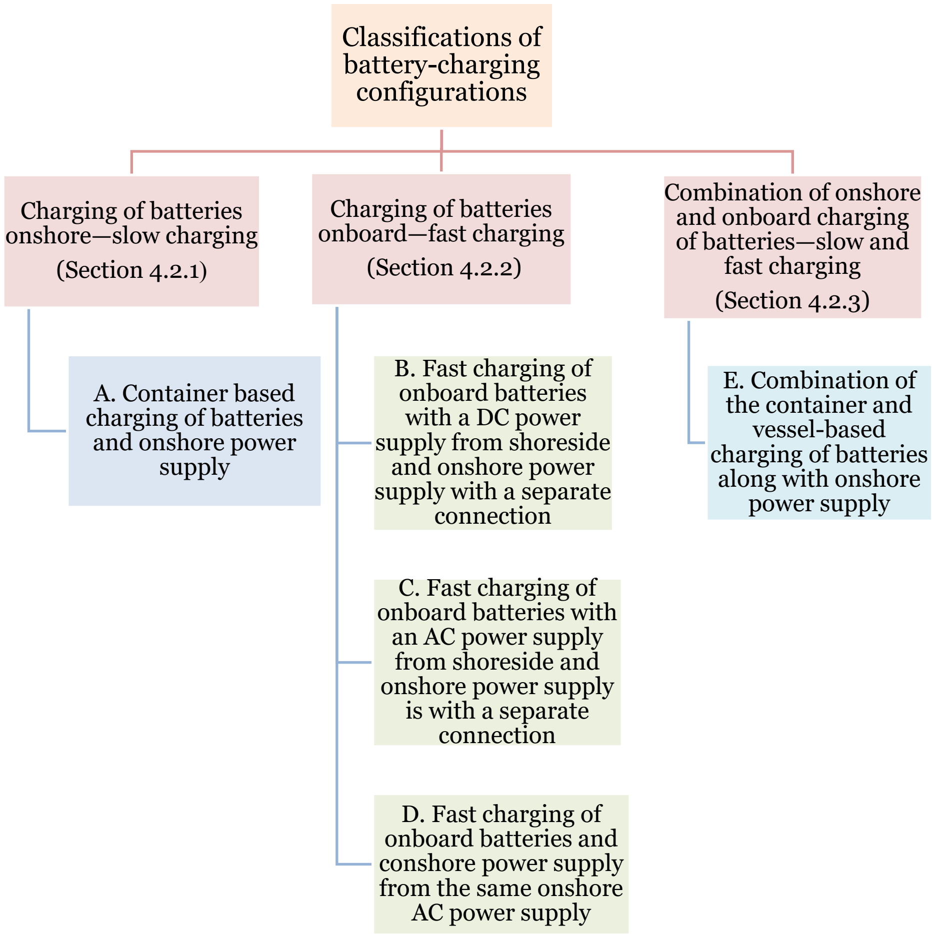


Figure 8. Classification of battery-charging configurations: onshore (slow), on-board (fast), and hybrid (slow and fast) (Publication-III)

4.2.1 Charging of batteries onshore – slow charging

This consists of only one configuration and it is explained as follows:

A. Container-based charging of batteries and OPS

Figure 9 shows configuration A. In this scenario, three batteries having power capacity of 2 MWh for each are shown inside three different containers on shore at the harbour. The onshore bus, which receives power from the 0.69 kV port bus (in the HASG) through a step-up transformer (T5), supplies the onshore power at 6.6 kV. Through a step-down transformer (T6), the 20 kV harbour area bus (in the

HASG) provides power to the 0.69 kV charger bus for charging batteries. For the purpose of charging the batteries in the containers, power electronic converters on the shore-side convert 0.69 kV AC to 0.69 kV DC (maximum). In order to charge each BESS having nominal voltage of 0.6 kV, a constant DC current of 290 A is used; this results in a rise in BESS voltage that is dependent on the SOC; the maximum voltage at 100% SOC is 0.69 kV DC. A typical slow charging time considered for the batteries is 10 hours. When the vessels are docked for OPS, the discharged batteries are swapped out with the charged ones from shore-side containers. The main characteristic of this configuration is that the batteries can be charged during off-peak hours at a lower cost and with less power than in other configurations.

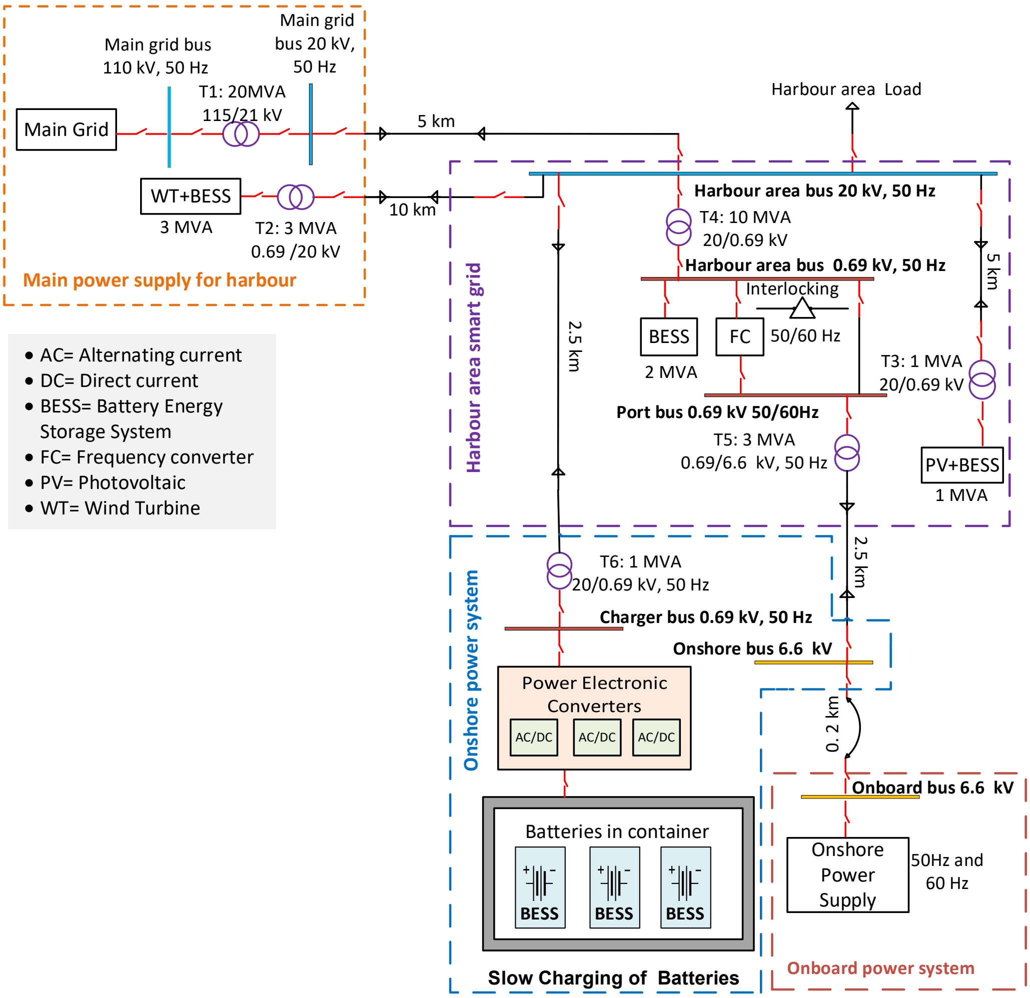


Figure 9. Configuration A: Container-based charging of batteries and OPS (Publication III)

4.2.2 Charging of batteries on-board – fast charging

In the examples of vessel-based charging configurations, three on-board fixed batteries inside the vessel, each with a power capacity of 2 MWh, have been studied. Each BESS, which has a nominal voltage of 0.6 kV, is charged with a constant DC current of 1450 A. This produces a voltage that varies depending on the SOC of the BESS, with a maximum of 0.69 kV DC at 100% SOC. During the ship's stay in port, the batteries are charged in two hours using a fast-charging mode. In this type, the following three configurations for fast charging have been analysed, which vary in the power supply arrangement for OPS and the battery-charging layout to the vessel. However, the same charging methodology is employed in the following three configurations B, C and D.

B. Fast charging of on-board batteries with a DC power supply from the shore-side and OPS with a separate connection

In configuration B, as shown in Figure 10 OPS is supplied with AC power and battery-charging power is supplied independently with DC power from the 0.69 kV port bus and 20 kV harbour area bus, respectively. A transformer (T6) was used to transform electricity from the 20 kV harbour area bus to 0.69 kV AC, and further power electronic converters converted to 0.69 kV DC (maximum) for charging batteries on-board. This charging scenario is characterised by the availability of shore-side DC power supply, which simplifies charging by eliminating the need to convert AC to DC power on-board. Consequently, only DC–DC power electronic converters are required on-board the vessel to control the charging voltage.

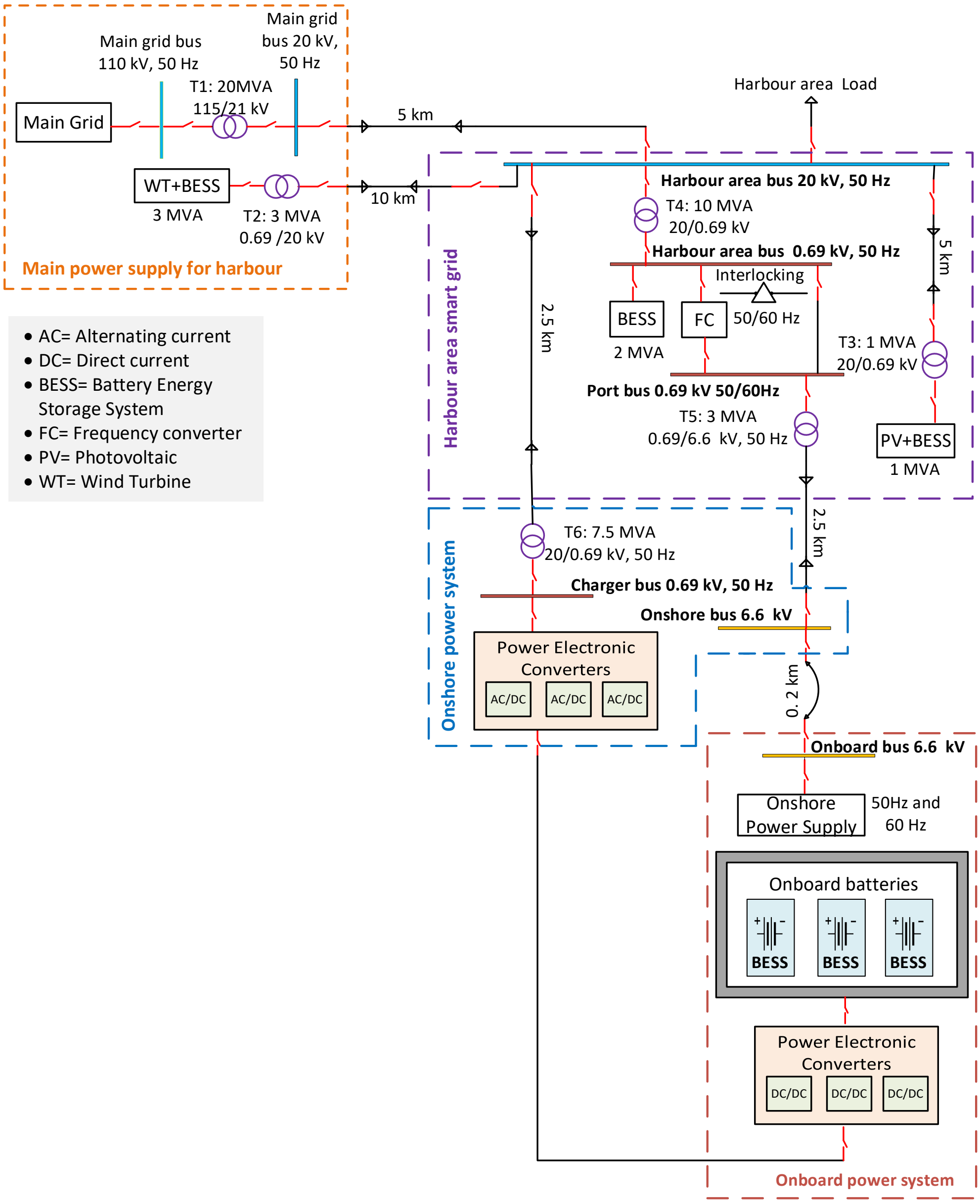


Figure 10. Configuration B: Fast charging of on-board batteries with a DC power supply from shoreside and OPS with a separate connection (Publication III)

C. Fast charging of on-board batteries with an AC power supply from the shore-side and OPS is with a separate connection

In configuration C, as shown in Figure 11, 0.69 kV port bus and the 20 kV harbour area bus supply power to separate AC connections for supplying OPS and charging the batteries respectively. The 20 kV to 0.69 kV step-down transformer (T6) and the required power electronic converters (0.69 kV AC to 0.69 kV DC maximum) for charging batteries were placed on-board. The most important aspect about this configuration is that it saves space in harbours because it does not need any charging equipment on the shore.

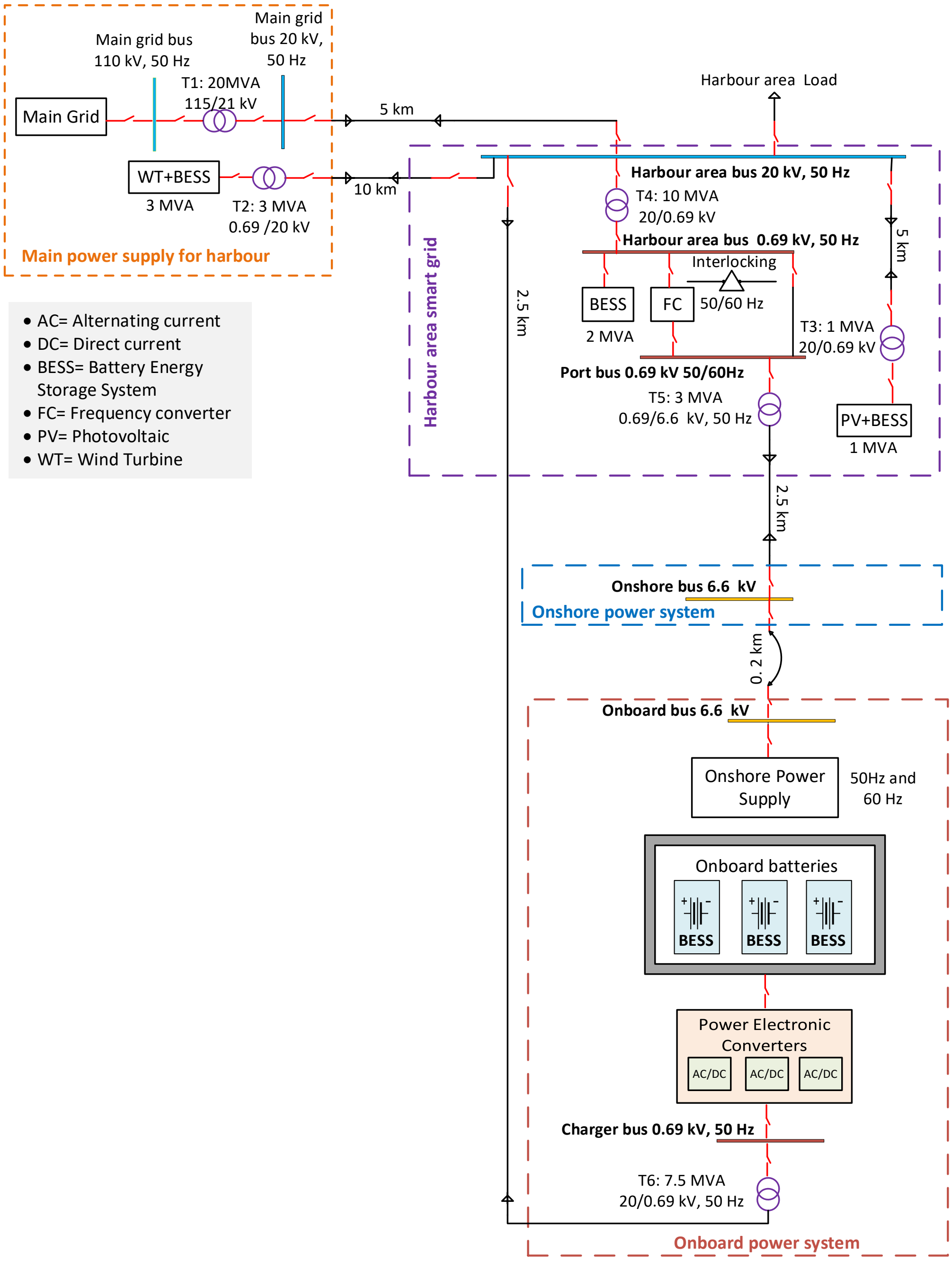


Figure 11. Configuration C: Fast charging of on-board batteries with an AC power supply from shoreside and OPS with a separate connection (Publication III)

D. Fast charging of on-board batteries and OPS from the same onshore AC power supply

In configuration D, as shown in Figure 12, both OPS and on-board battery charging are through a single 6.6 kV connection (from the harbour area bus, 0.69 kV, 50 Hz) by a step-up transformer (T5, in the HASG). The transformer (T6) on-board the vessel lowers the voltage of 6.6 kV to 0.69 kV AC, which is then transformed to 0.69 kV DC (maximum) for charging batteries.

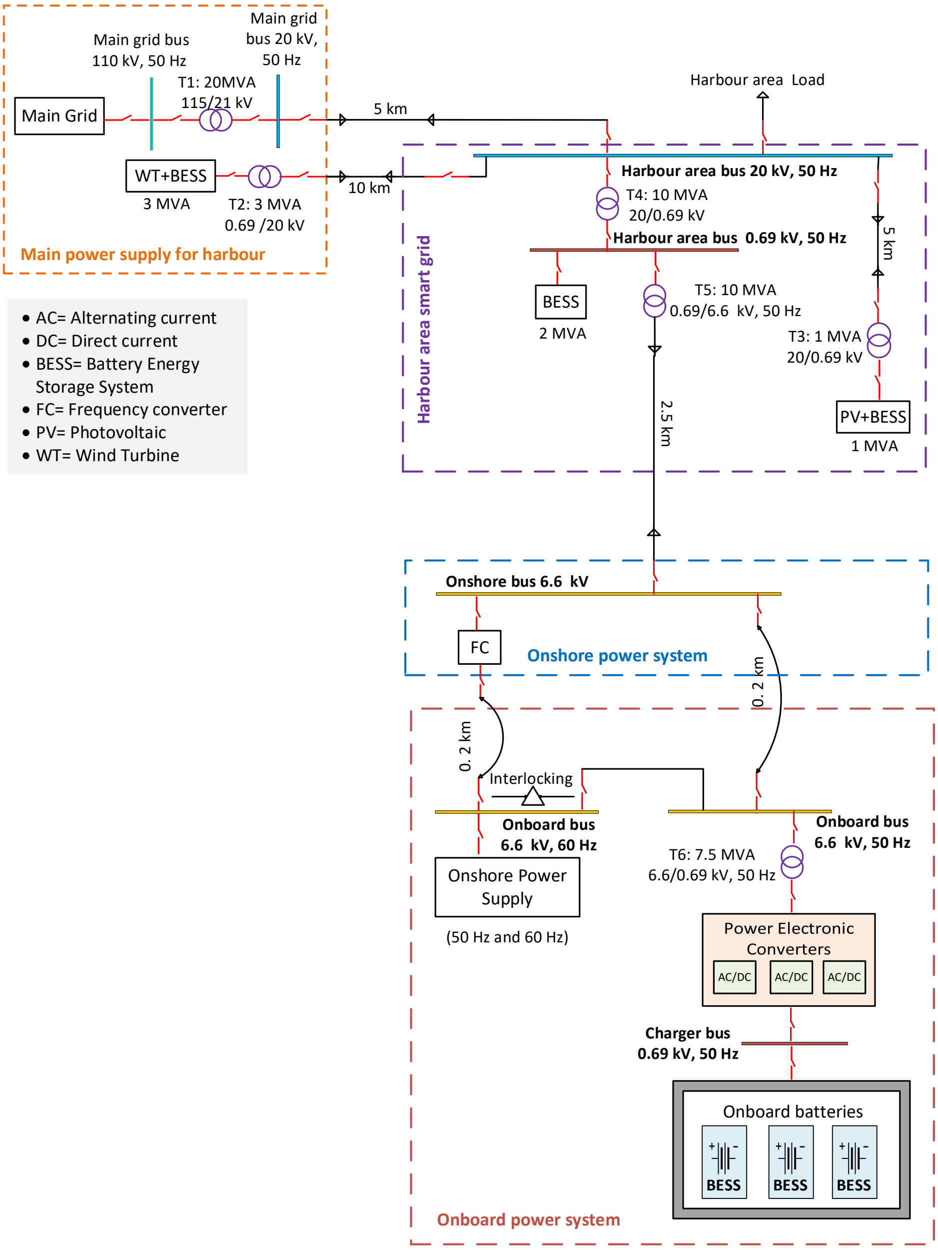


Figure 12. Configuration D: Fast charging of on-board batteries and OPS from the same onshore AC power supply. (Publication III)

The position of the frequency converter is the main distinction between this charging configuration and the others. It is neither possible to use a single power supply connection for battery-charging nor the frequency converter because the harbour grid is initially assumed to be at 50 Hz (Figure 9), and the frequency converter has a power capacity sufficient only for the 60 Hz OPS. The frequency converter is one of the most expensive pieces of equipment in the harbour grid; thus, expanding its power output to meet both types of load is not an economically viable solution.

In configuration D, the frequency converter is now situated between the onshore bus and the on-board vessel power system (Figure 12) rather than its previous connection between the harbour bus and the port bus (Figure 9). Consequently, it is no longer necessary to use the port bus and the associated switchgear and protection equipment. The interlocking switch is set up so that the OPS for the docked vessels can be either 50 Hz or 60 Hz; however, this configuration can supply both OPS and the battery-charging load with a single connection only, assuming the same power frequency for power systems of harbour grid and on-board vessel. Otherwise, separate connections would be required.

4.2.3 Combination of onshore and on-board charging of batteries—slow- and fast-charging

This consists of only one configuration, and it is explained as follows:

E. Combination of the container and vessel-based charging of batteries along with OPS

Configuration E is combining vessel-based and container-based batteries, as shown in Figure 13. It consists of three onshore batteries in containers and three batteries permanently installed in the vessels, each with a nominal voltage of 0.6 kV and a capacity of 2 MWh. The transformer (T6) transformed 20 kV to 0.69 kV AC. Power electronic converters converted to 0.69 kV DC (maximum) for charging the batteries in the shore-side containers. At 100% SOC, the shore-side batteries are charged with a steady 290 A DC current to a maximum voltage of 0.69 kV DC. The shore-side batteries are charged within 10 hours, which is considered slow charging; however, the fixed vessel batteries are charged from the shore-side batteries within 2 hours, which is considered fast-charging, while the vessel is docked. At 100% SOC, fast charging was performed with a constant current of 1450 A DC to a voltage of 0.69 kV DC (maximum). This design can be described as a dual charging with both slow and fast modes of battery charging.

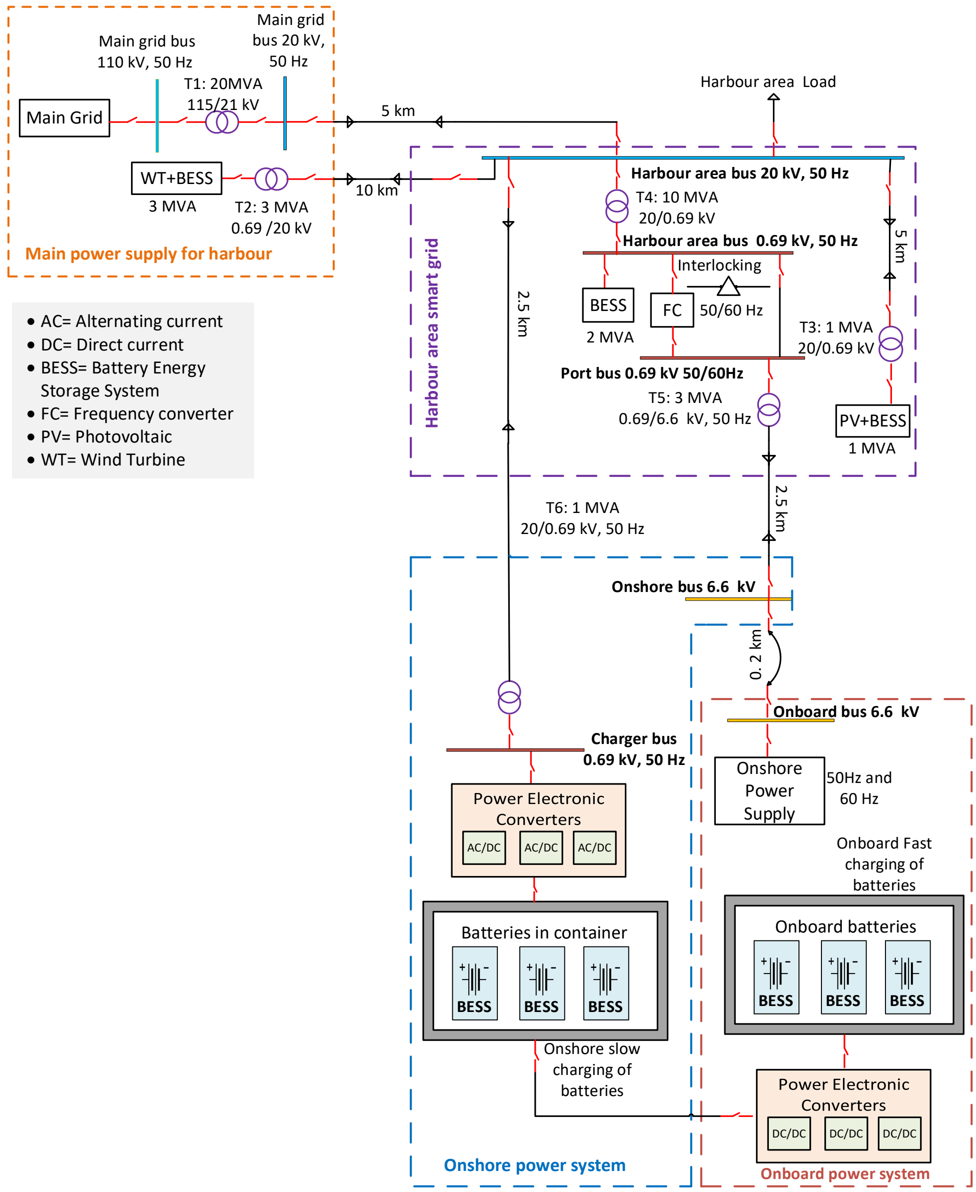


Figure 13. Configuration E: Combination of the container- and vessel-based charging of batteries along with OPS. (Publication III)

4.3 Comparisons of different types of battery-charging configurations

A comparison based on the technical aspects of each battery-charging configuration is shown in Figure 14.

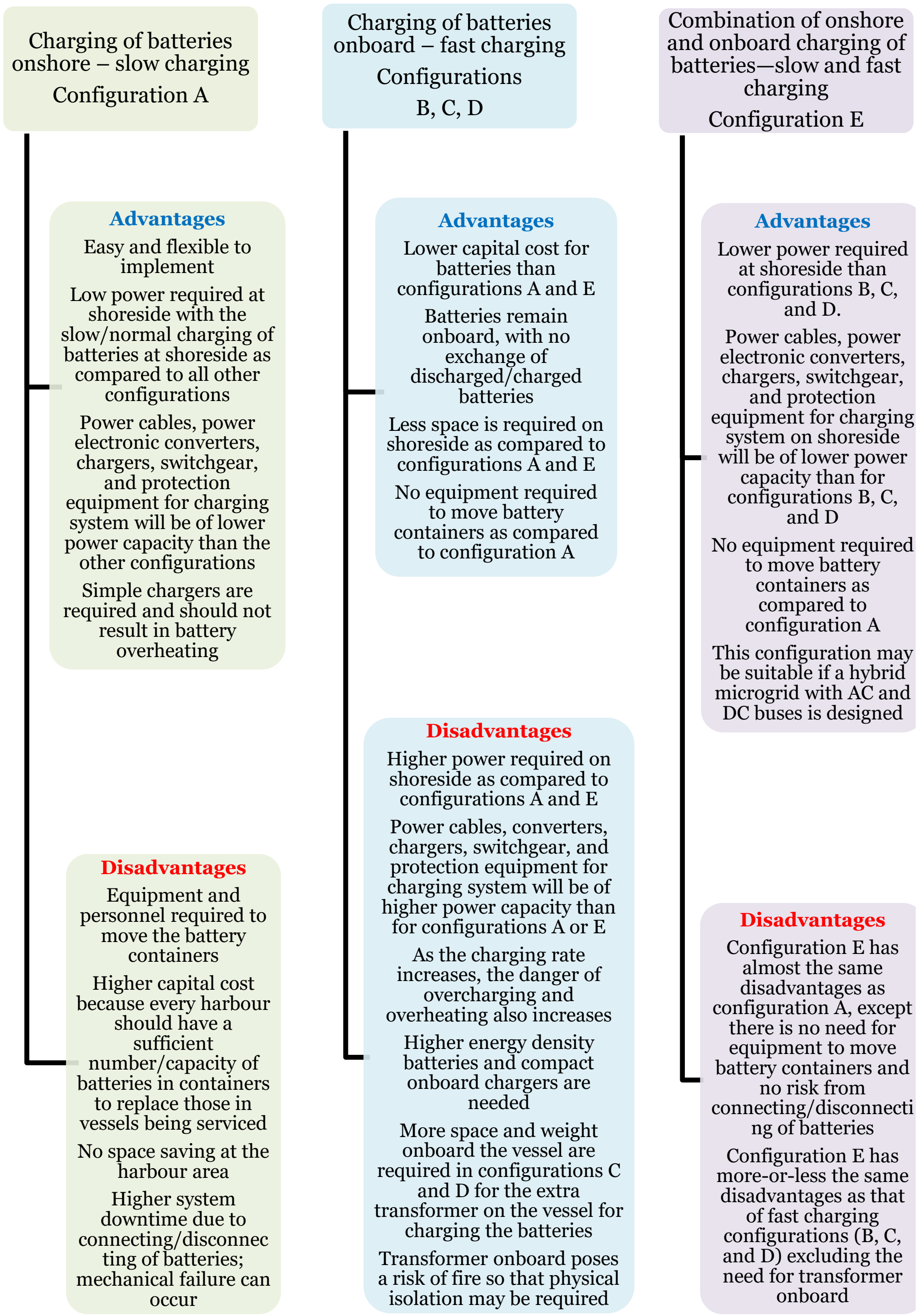


Figure 14. Comparisons of the battery-charging configurations

Each configuration has some advantages and disadvantages over other configurations depending upon cost, available space at harbours and vessels, and etc. Though difficult, this comparison helps understand the appropriate configuration for any specific harbour grid.

4.4 Simulation results

The technical feasibility of these configurations is verified through the detailed simulation results presented in Publication III. The results exhibit slow- and fast battery-charging configurations (configuration A and configuration D). In these simulations, time-varying dynamic load is considered for an OPS of 2 MW maximum power. The nominal battery-charging loads of 0.7 MW (at a charge rate of 0.1 C) and 4.5 MW (at a charge rate of 0.5 C) are considered for simulating configuration A and configuration D respectively. Figure 15 shows the rate of change of SOC for configuration A and configuration D based on the sampled time of 20 seconds at initial SOCs of 25%, 50%, and 75%. Moreover, the results indicate that both slow- and fast battery-charging configurations are capable enough to charge within 10 hours and 2 hours, respectively, and the fast battery-charging configuration charges five times faster than the slow battery-charging configuration.

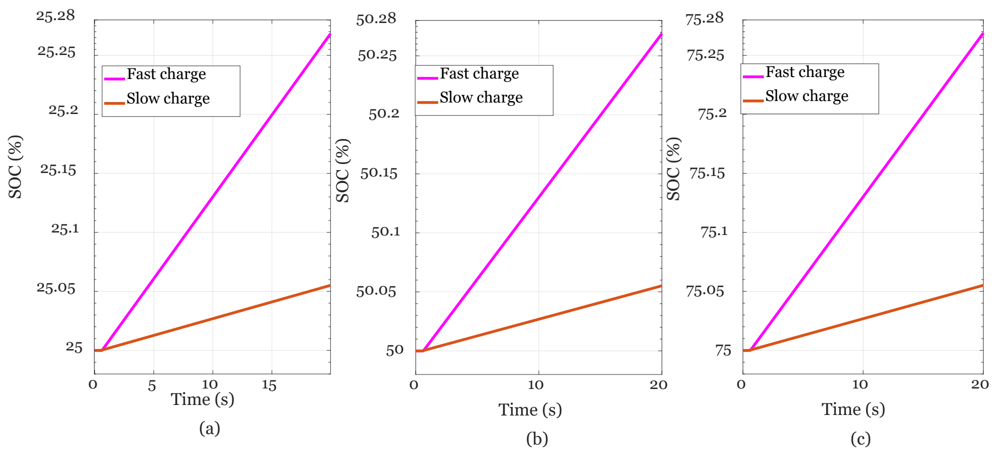


Figure 15. Rate of change of SOC of batteries in configurations A and D (Publication III)

It was observed from the simulation results that the maintaining all bus voltages in slow-charging model (configuration A) was achievable because of separate connections for OPS and battery-charging loads. However, maintaining voltage at all buses in the fast-charging model (configuration D) was a challenging task due to large power demand with a single connection for both OPS and battery-charging loads.

Figure 16 shows the dynamically varying voltages at Onboard bus 6.6 kV, which is due to time-varying OPS along with battery-charging loads. The dotted lines highlight time steps at which dynamics in voltages occur, owing to switching transients caused by variation in the status of the load demand. In this simulation, a maximum load of OPS for a certain seaport is taken as (2 MW + j0.3 MVAr). The load of OPS with a half of its maximum power demand was initially connected at (1 MW + j0.15 MVAr), and at t=0.6 second, momentary rapid changes in voltage occur caused by switching transients, when the fast charger load of 4.5 MW is connected. The time-varying load of OPS varies as follows: decreased to (0.5 MW + j0.075 MVAr) at t = 5 seconds, increased to a maximum load (2 MW + j0.3 MVAr) at t = 10 seconds, and finally disconnected at t = 18 seconds. There could be several ways to maintain the voltage, but an on-load tap changer on transformer T1 was considered as an economically viable solution to maintain voltage whenever dynamically varying OPS load causes a drop at the on-board bus. The simulation results show that the voltage levels for slow- and fast-charging (configurations A and D, respectively) are within the specified limits of the HVSC standard. The simulation results validate that the designed HASG configurations meet the required slow and fast battery charging demands of modern vessels and thus can be implemented in practice.

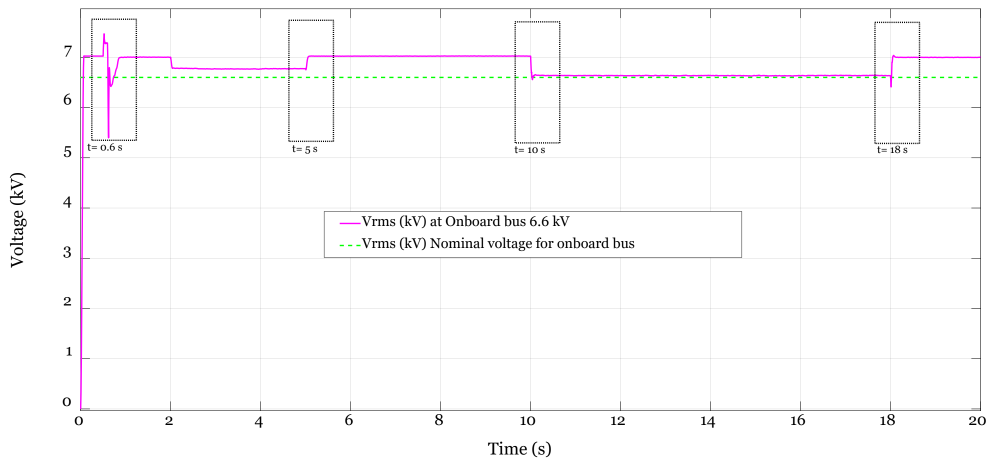


Figure 16. Voltage and power at onboard and charger buses in configuration D (Publication-III)

4.5 Summary of the chapter

Based on Publication III, this chapter investigates battery-charging configurations for HASG that can facilitate different types of modern ships at seaport harbours. A literature review shows that this research is the first attempt to systematically evaluate alternative ways of battery-charging configurations in harbour grids. Each configuration has its own significant advantages and disadvantages in terms of space availability either on shore or ships as well as economic and technical viability. Based on the available infrastructure in harbours and the requirements of different types of ships, an appropriate charging configuration can be preferred. Two battery-charging configurations were developed in PSCAD software: a slow- and fast-charging configuration; their performance was validated using simulation tests as presented in Publication III. Those two battery-charging approaches can be applied for both hybrid and electric vessels. These insights serve as a basis for ship owners to develop appropriate business models and for port administrators to encourage the use of BESS in the marine industry.

The slow-charging configuration is a viable option for a harbour with low-power capacity and ships with limited on-board space. On the other hand, the fast-charging configuration is suitable for a harbour with high-power capacity or ships with limited docking space. Slow charging, on the other hand, may also be desired because fast charging rates lead to more power lost as heat, which is not recovered anymore. In the future, a configuration that combines slow- and fast-charging approaches (configuration E) would be a useful alternative, when considering a hybrid microgrid for a harbour. This solution is appropriate for harbours that have low-power capacity and vessels that require fast-charging, especially if space on-board and shore-side are not a major issue. In the future, a hybrid microgrid containing combined slow- and fast-charging configurations together can be evaluated in detail. Though expensive, it provides the advantages of both slow- and fast-charging.

5 SIZING AND ALLOCATION OF BATTERY ENERGY STORAGE SYSTEMS IN HARBOUR GRIDS

This chapter explains the importance of integrating RESs and allocating BESS into harbour grids to satisfy the growing power and energy demand of modern electric and hybrid vessels docked at seaports. Based on Publication IV, this chapter first introduces a methodology for sizing and allocating BESS in harbour grids, and then it applies this approach by simulating two case studies of real-world harbour grids in the Åland Islands. The results demonstrate that with the applied approach, the proper sizing and allocation of BESS can be achieved in any operating harbour grids planning for integrating RESs on a large scale. This chapter covers one of the key contributions of the dissertation by demonstrating that proper sizing and allocation of BESS are necessary in order to compensate the intermittent nature of the power generated by RESs, shave peak-load demand and avoid the expansion of the power capacity of any operating harbour grid. This chapter addresses the following research question:

RQ3: How to solve the challenging issue of appropriate battery sizing and allocation at different nodes of the distribution system connected with the harbour grid, that deals with growing power demands and integration of RESs?

5.1 Integration of renewable energy resources and battery energy storage systems in harbour grids

Reliance on RESs is growing in the electrical power sector as a result of growing environmental concerns and increased knowledge of climate change (Hameed et al., 2021)(Baumgarte et al., 2020). The use of RESs in maritime systems, such as seaport microgrid, increases the energy efficiency and decreases fossil-fuel usage, which reduces the environmental threat. The most significant step towards achieving zero emissions is electrification of seaports. In an effort to reduce emissions, many countries with lengthy coasts are striving to establish plugged-in battery-powered ferry operations and expand supporting infrastructure. However, the high intermittency and limited possibilities of dispatching power from RES-based power plants impede smooth transition towards sustainable energy solutions. ESSs, particularly the BESSs, are supposed to be a viable solutions to deal with these problems (Hameed et al., 2021)(Baumgarte et al., 2020).

To meet the existing and future energy requirements, harbour grids may need to expand for accommodating the significantly higher load demands of the FCSs. Typically, new power lines are constructed to support growing plans for power demands. However, the expansion cannot generally occur promptly since the installation of new lines requires resources and approval from the concerned authorities, which can delay development (Aguado et al., 2017). Compared to installing new transmission lines, ESSs are significantly simpler to install (Poullikkas, 2013) and have already demonstrated some cost benefits when the transmission line upgrades are deferred, as mentioned in (Malhotra et al., 2016). In market-driven energy systems, expanding the power grids with BESSs is a promising approach. Despite the high expense of batteries, a study made by Aguado et al.(2017) indicates that expanding the power system with BESS is still advantageous because it can delay the need to construct new transmission lines. The BESS can be placed at both medium- and low-voltage grid levels for a variety of applications and incorporate a large proportion of RESs. As also explained in Publication IV, harbour grids that support the heavy load demands of FCSs and OPS for modern vessels would incorporate high penetration of RESs and BESS, as shown in Figure 17. Moreover, designing a suitable size of BESS at proper location is indispensable for any operating harbour grids.

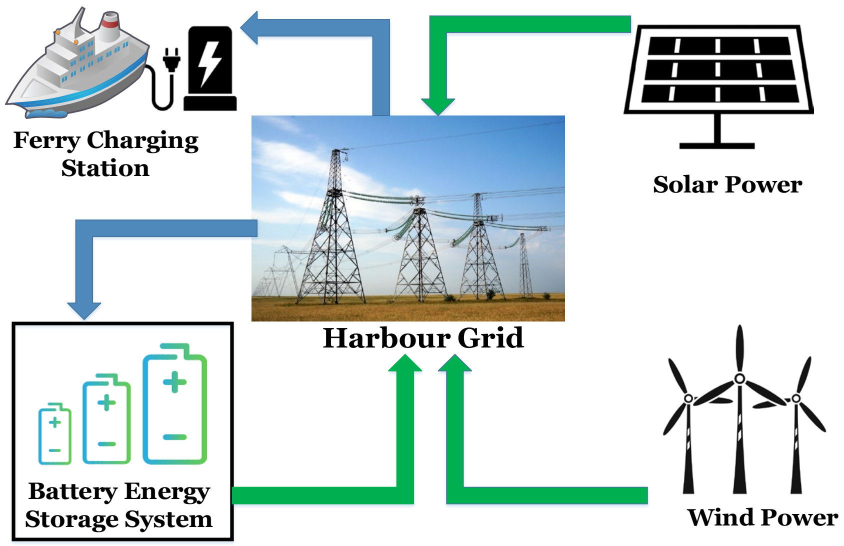


Figure 17. Integration of renewable energy resources and battery energy storage systems in harbour grids

BESSs are becoming increasingly important in the transition to low-carbon power systems; however, their implementation in projects of the electrical power system is impeded by their economic viability. Private, commercial, and institutional investments in large-scale BESS projects are required to drive the expansion of the BESS industry (Hameed et al., 2021). The BESSs can store energy when prices are low and supply it to the power grids when prices are high; thus, their usage in expansion projects improves net social welfare. The main advantages of utilising

BESSs include their fast response time and high-energy efficiency, which enables them to be an appropriate solution in almost all ESS applications. However, they also have disadvantages, such as shorter life span, a high cost, a lot of maintenance and sensitivity to heat. (Aguado et al., 2017).

The impact of new transmission lines and BESSs in the power grids is taken into account in a mathematical model for the transmission expansion with ESSs for market-driven applications proposed by Aguado et al. (2017).. The study has determined that it is possible to postpone the expansion of new transmission lines if BESSs are added to certain nodes. From a business perspective, the problem of placing BESS is solved by conducting a stage-level analysis of BESS projects (Hameed et al., 2021). The authors Boveri et al. (2019) present a strategy for the optimal selection, sizing, and administration of ESSs according to the goals of economical generation and consumption of electrical energy for shipboard power systems. They propose an approach for selecting the optimal size of an ESS (e.g., BESS, flywheel, or super capacitor), based on a typical shipboard load power profile. This optimal selection and sizing has to take into account the optimum power generation and the aging effect on the storage system. The method of experimentally determining the charging and discharging characteristics of the BESS located in a real VPP in Poland is presented by Kaczorowska et al. (2020), which can also be employed for other BESS, including any other ESS. A method for optimally sizing LIB is proposed by Han et al.(2022), which considers the non-linear features of LIB using Peukert's law and the assessed load conditions in terms of the size of BESS. The case study of Copenhagen, Denmark by Ahamad et al. (2018) has optimally sized integrated RESs at seaport and concluded that WT, PV, BESS, converter and grid connections are the most cost-effective solutions for supporting environmental sustainability. Uwineza et al. (2021) have analysed the feasibility for the integration of RESs into the energy grid of Popova Island, and they have implemented the Monte Carlo method. After an analysis, they then evaluated the financial outcomes. This literature review reveals a lack of research papers that assess the actual charging and discharging characteristics of BESS facilities as well as models based on those characteristics, particularly in the power systems industry (Kaczorowska et al., 2020).

Although many researchers have considered the integration of RESs and BESSs for shipboard power systems, relatively few researchers have considered them for harbour grids. No one has yet discussed the size and location of BESSs for harbour grids. It is a challenging task to design an appropriate size and location of BESS while simultaneously integrating RESs on a large scale and accommodate the needs for the FCSs because both oversized and undersized BESSs would result in power loss and frequency deviation, respectively, as well as fail to balance supply and demand (Wali et al., 2022).

Despite numerous research studies that evaluated shipboard and harbour grid power systems, Publication IV first attempted to overcome the challenging task of the sizing and allocation of BESSs for any operating harbour grid operation. Therefore, the key contribution of Publication IV is the development of an algorithm that determines the appropriate size and power capacity of BESSs for any harbour grid that also plans to integrate RESs, electric ships and FCSs locally without expanding the power capacity of transmission lines and other grid components. In a real-world scenario analysed in Publication IV, namely the Åland Islands power system, was tested in order to evaluate the proposed method. Based on this system as published in Publication IV (2020), two future case studies were modelled in PSCAD software, which anticipated a considerable amount of RESs for the horizon years 2022 and 2030. First, the base cases for the years 2022 and 2030 were modelled in such a way that maximum loading and minimal generation levels from the integration of RESs without BESSs for the corresponding years were considered. In the next step, base case simulation results were compared to the appropriately sized and located BESS simulations results. Consequently, with proper sizing and location of BESS, the results indicated that it is possible to avoid the expansion of the power capacity of electrical equipment, such as transmission lines, transformers and other protective devices in the Åland electrical network.

5.2 The proposed method for sizing and allocation of battery energy storage systems in harbour grids

Publication IV proposed a technique for BESS sizing and allocation to alleviate line congestion for harbour grids that results in capital cost deferral. The BESSs were considered as the primary sources of flexibility resources in power system operations. This section presents an overview of the features and performance of LIBs, outlining their ability to function as a resource for short-term flexibility in smart grids. In addition, it also demonstrates that an equivalent circuit battery modelling method is required to appropriately model the behaviour of LIB due to its highly non-linear voltage and current characteristics. Next, an algorithm to size and allocate BESSs for the steady operations of weak harbour grids is developed to accommodate for fluctuations imposed by higher penetration of RESs and power consumption changes.

The LIBs are the most appropriate electrochemical energy storage technology for medium voltage shore connection applications, and their incredibly long lifespan makes them useful for a high number of daily cycles (Vicenzutti & Sulligoi, 2021). Grid-connected lithium-ion BESS design and implementation are challenging tasks due to the many factors that need to be taken into account, such as economic feasibility, environmental considerations, power and frequency control, and characteristics of battery (Wali et al., 2022). If BESS is designed to supply less power than the power demand, it will be consumed beyond the designed safety range, and waste residual energy will be produced. However, if a BESS is designed to supply more electricity than is required, an additional capital and maintenance costs will be incurred (Han et al., 2022).

Increasing interest in fast controlled lithium-ion BESSs for flexible energy needs is due to their advantages: technological improvements and declining prices. Mostly, the literature considers BESS to be an ideal DC voltage source (Chauhan et al., 2019) or employs mathematical modelling methodologies, but accurate modelling of BESS for stationary energy storage grid applications is limited. The first math-based kinetic battery models (KBM) for lead-acid batteries has been proposed by Tariq et al., (2018). The Modified KBMs (Bako et al., 2019) are often used to simulate LIBS for smart grids; however, KBMs do not account for the non-linear features of LIBS, which are affected by multiple operating factors including SOC, current rate, temperature and age.

Physics-based electrochemical models can accurately model battery cell internal behaviour (Ahmed et al., 2014), but it requires a tremendous amount of mathematical calculation, which makes their application in smart grid simulations virtually challenging. Integration of the equivalent circuit model (ECM) for electrical vehicle propulsion has been introduced by Chen & Rincon-Mora (2006), which assumes SOC as the major influencing factor. The ECM described by the authors Nadeau et al. (2013) explains battery characteristics of electric vehicle with regard to aging under world motorcycle test by one resistive-capacitive branch consisting of the internal resistance. The effects of physical phenomena such as SOC and temperature on the battery cell model have been investigated (Deng et al., 2017). Most of the BESS ECM models provided for power system simulations are lacking in one or more factors that determine the efficacy of LIBs.

When BESS models are accurate, battery design, sizing, optimisation of control and dispatch approaches are more likely to be successful. In addition, accurate battery performance models are essential since modern battery management systems rely on them to monitor the important characteristics of each cell and overall BESS. In Publication IV, the detailed ECM of lithium-ion BESSs as proposed by the authors Arunachala et al. (2016) is used to appropriately size BESS for multiple locations and substations in the Åland Islands as a case studies to mitigate network congestion and capital investments delays, in terms of expanding power grids.

Figure 18 proposes a method for sizing lithium-ion BESSs for weak harbour grid power systems to facilitate integration of FCS and RES. By deploying BESSs at critical locations with the proposed algorithm, Åland Islands can decrease or eliminate network congestion and capital investment to update existing power system infrastructure. The main input of this algorithm is line current data received from the base case studies of PSCAD simulations. The algorithm receives the line current (I_{LINE}) and its maximum line current capacity (I_{Max}) for each 45 kV transmission line as inputs. A power transmission line is not congested if $I_{LINE} < I_{Max}$ for that particular transmission line.

In contrast, if $I_{LINE} > I_{Max}$, then the transmission line is congested and BESS installation is required in a neighbouring substation. Moreover, sizing lithium-ion BESS appropriately for grid applications is essential when considering its economic and environmental impact on a project. The BESSs are accurately sized for power grid applications using the battery cell ECM model. In a subsequent part of the algorithm, BESS AC Voltage ($V_{AC,BESS}$) is provided as an input in order to calculate BESS AC Power ($P_{AC,BESS}$). In the following stage, the DC power requirements from BESS ($P_{DC,BESS}$) are calculated using the conversion efficiency (η=95%) of the power converter. In addition, the needed BESS nominal voltage ($V_{DC,BESS}$) and the corresponding power ($P_{DC,BESS}$) are provided as inputs to the developed ECM model. Performance-affecting parameters including temperature, age, SOC, and current rates are added to the BESS model based on a project's requirements. On the basis of $V_{DC,BESS}$ and $P_{DC,BESS}$, the battery size at a specific substation is determined. The size of BESS consists of the number of series cell connections (N_s) to achieve the desired nominal voltage levels and the number of parallel string connections (N_p) to achieve the requisite current-carrying capacity, nominal discharge power and energy characteristics, peak discharge power and energy, and nominal charging power demands. The algorithm then progresses to the next I_{LINE} input until all inputs have been processed. By employing this method at the needed substations, the optimal lithium-ion BESS size is determined. In addition, the designed BESS is assigned to the selected substations in the PSCAD model of the Åland Islands in order to conduct EMT simulations and record I_{LINE}. If the transmission lines are still overloaded ($I_{LINE} > I_{Max}$), the process depicted in Figure 18 must be repeated until the appropriate BESS size is determined.

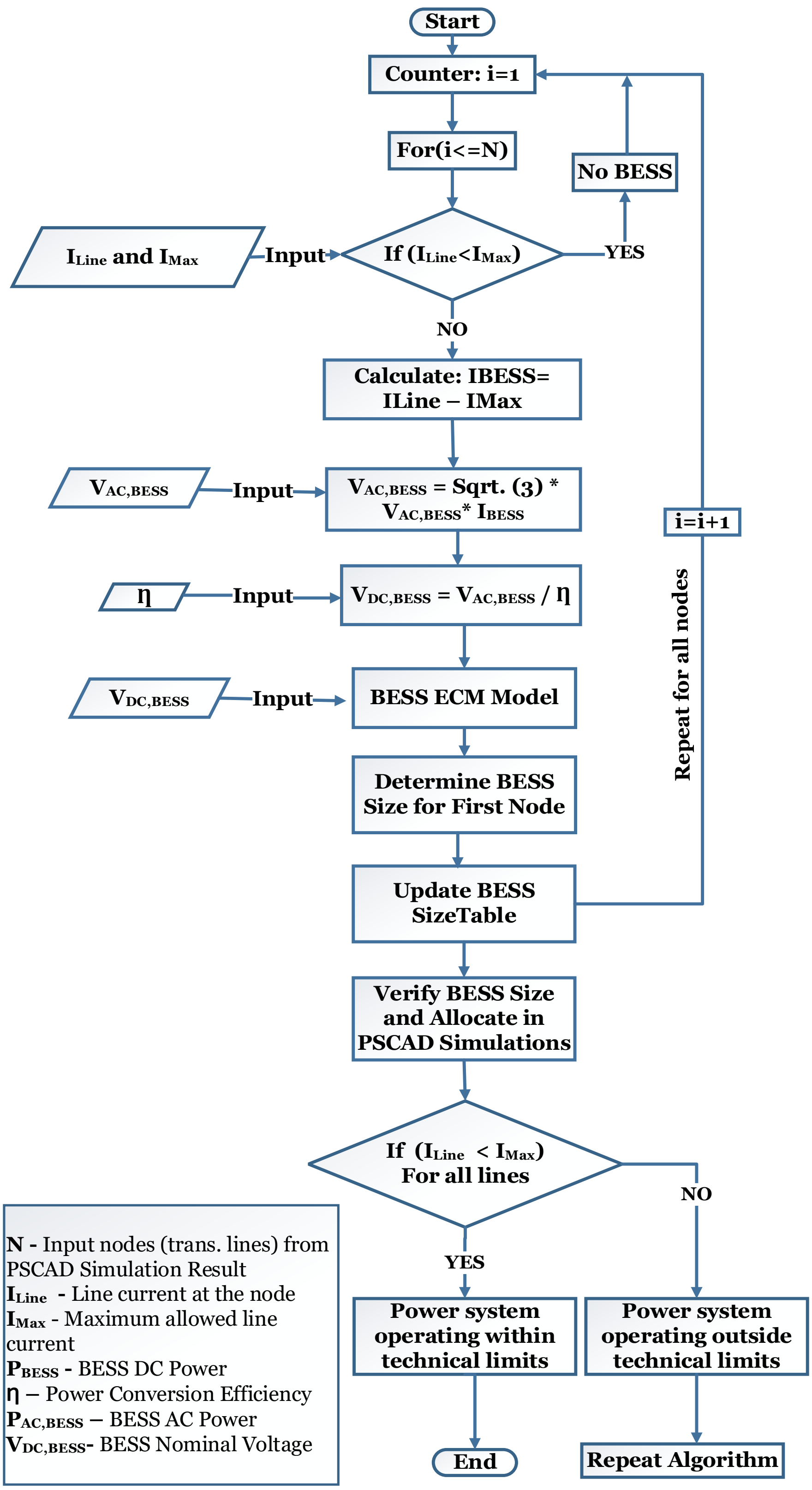


Figure 18. Battery-sizing and allocation algorithm (Publication IV)

5.3 Test system of harbour grid in Åland Islands

This section outlines a real-world test case of the harbour grid in the Åland Islands, which is simulated by considering potential future goals of integrating more FCSs and RESs along with BESSs for the years 2022 and 2030. Publication IV provides a comprehensive analysis and discussion of the simulation results.

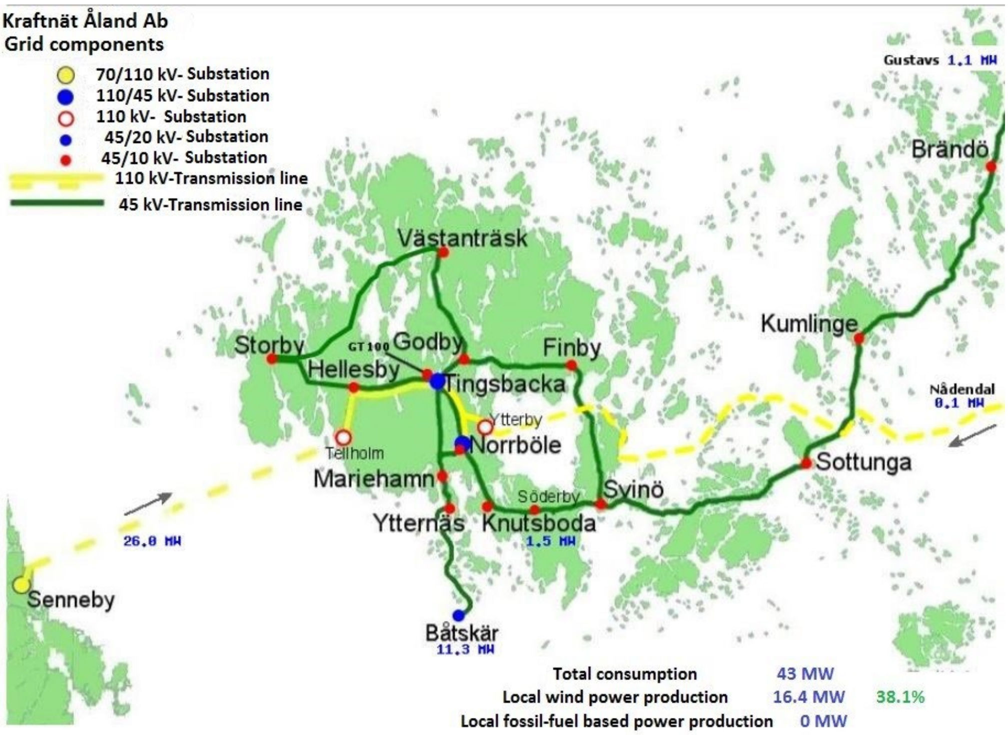


Figure 19. The geographical location and grid structure of Åland Islands (Publication IV)

Harbour grid in Åland Islands is situated in the Baltic Sea in Finland, and the geographical location is shown in Figure 19, while Figure 20 depicts its simplified single-line diagram. There are two 110 kV power transmission lines supplying power from Senneby (Sweden) and Nådendal (Finland). In addition to 110 kV transmission lines, Båtskär (WT Park) and Gustavs supply two additional 45 kV transmission lines (Finland). The primary power source for the entire network comes from the high-voltage AC transmission line at Senneby, while the high-voltage DC transmission line at Nådendal serves as a backup. Due to the intermittent nature of wind power generation, Båtskär and Gustavs have weak grid connections. Although the Föglö substation is not yet operational, it will be installed between the Svinö and Sottunga substations while considering future marine load requirements and the integration of RESs. In order to provide marine and other harbour loads, each 45 kV substation is connected to a 10 kV substation through step-down transformers of 45/10 kV. The Åland Islands grid is a relatively small and weak power system, with several medium-size or small port locations for future FCSs, and it has potential for integrating a large number of RESs. The transport between several islands is accomplished by electric ferries. Typically, Sweden and Finland supply power to the Åland Islands grid.

The Åland power system consists of several substations with varying load demands and has the possibility of more than one topologies for connecting one substation to another. Regarding future load demands, Åland Islands stakeholders aim to incorporate a significant quantity of RESs (PV and WTs power) in the years 2022 and 2030 in order to electrify transportation on the main island and between various islands. This development will start in two phases for the years 2022 and 2030 to accommodate an increase in the penetration of RESs and demand for electricity by electric ferries and ships that need to charge their on-board batteries at harbours and require OPS.

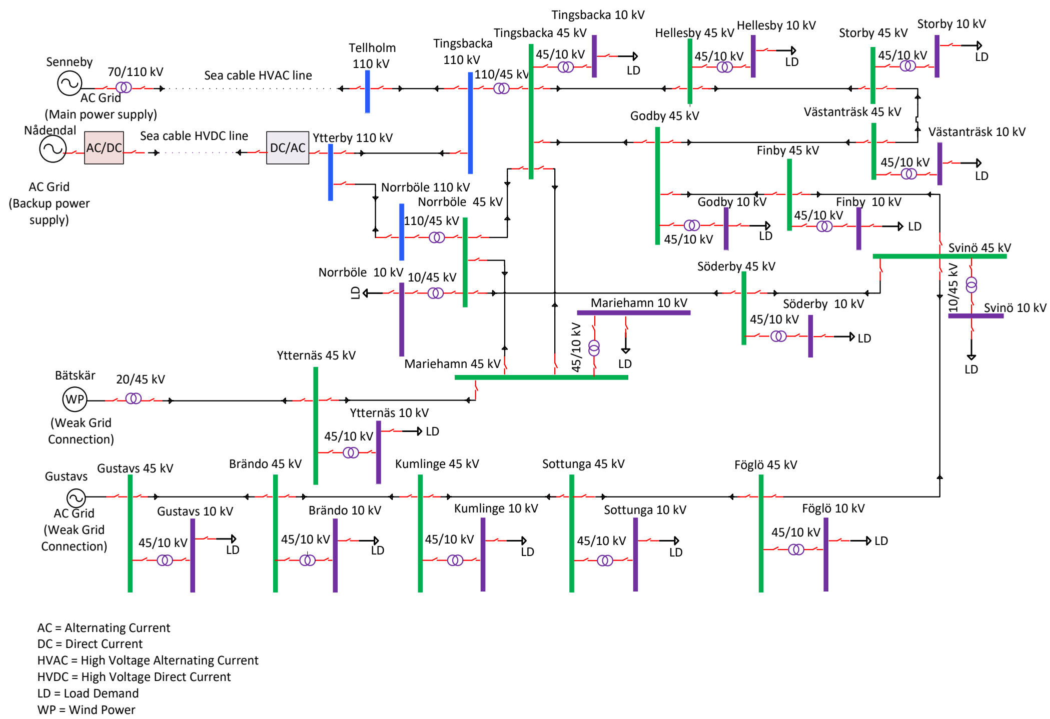


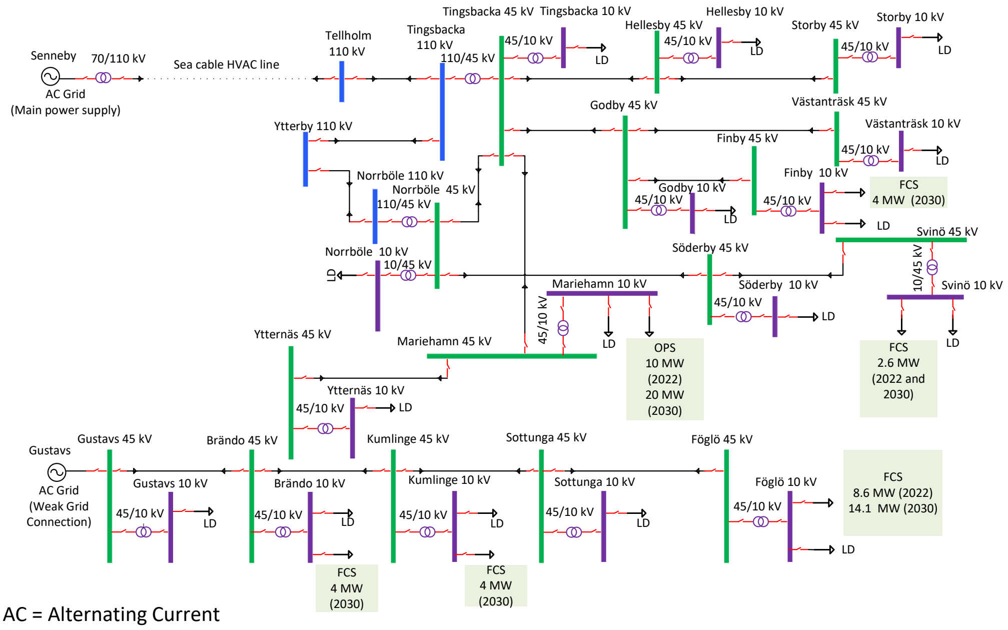
Figure 20. Single -line diagram of the Åland Islands power system (Publication IV)

Publication IV details models for the base case and two future case studies for the years 2022 and 2030 that have been developed and simulated in PSCAD for analysing the impact of integrating BESS. The base case simulation model simulates maximum loading for the years 2022 and 2030, but it does not account for the integration of RESs and BESS. However, for the case studies of the years 2022 and 2030, simulation models analyse the deployment of BESS and demonstrate the impact of integrating a minimal and maximum quantity of BESS on network topologies.

5.4 Simulations of Base Case Studies for 2022 and 2030 without BESS

The base scenario is simulated to examine how the power system of the Åland Islands operates for the anticipated marine load requirements of FCSs and OPS in the years 2022 and 2030 without integrating RESs and BESSs. This enables to identify which transformers, transmission lines, and other electrical components are overloaded. Publication IV aims to design the BESSs of appropriate sizes and allocate them at the relevant substation and focuses on details concerning transmission line overloading and voltage levels at all 45 kV substations. The power system in the Åland Islands is typically operated as a radial network with the following circuit breakers in the open position between substations: Västanträsk and Storby; Finby and Svinö; Svinö and Föglö; and Norrböle and Mariehamn.

In the simulation model of the Åland power system, the minimum generation and maximum loading scenarios for 2022 and 2030 are simulated in such a way that Båtskär and Nådendal are not operational. Figure 21 depicts the single line diagram of simulation model, which considers the aforementioned operational criteria as well as the expected load demands for 2022 and 2030. Therefore, two alternative islanded sections of the network with radial topologies are being formed by the way the power system in the Åland Islands is currently operating. The expected maximum capacity of power output from PV sources in 2022 is 33 MW divided by 3 MW equally at each of the 10 kV substations and 30 MW of WT power generation at the Tellholm substation, totalling 63 MW. While for the year 2030, there will be 10 MW more solar power at Hellesby, 15 MW more in the power capacity of WT power generation already installed at Tellholm, and 118 MW more of WT power at Föglö. This will result in a 143 MW additional capacity of power generation from the integration of RESs in 2030, when compared to the 2022. Thus, the grid power supplied by the Senneby, Nådendal and Gustavs substations will be replaced by the huge amount of power produced by RESs. Due to the intermittent nature of RESs, the base case simulation demonstrates that it is difficult to ensure an uninterrupted power supply. As a result, it provides a basis for installing appropriately sized BESSs in suitable places for stable grid operation. Additionally, the BESS are designed to be charged during off-peak hours, particularly from local power generation from RESs, and discharged anytime when there is a peak load demand.



AC = Alternating Current
FCS = Ferry Charging Station
HVAC = High Voltage Alternating Current
LD = Load Demand
OPS = Onshore Power Supply

Figure 21. Single -line diagram of the electricity network in the Åland Islands for base case studies without BESS (Publication IV)

First, the detailed model of the Åland Islands electricity network is simulated in PSCAD for the base case without BESS. The line currents and their maximum current-carrying capacity are then fed into the developed algorithm in MATLAB/Simulink, which is used to accurately size BESS as described in Section 5.2.2. Additionally, several methods are used to control reactive power, ensuring that the voltage at various substations remain within limits, as shown in Figure 22. However, Figure 23 depicts that the current flowing at some lines exceeds the maximum current-carrying capacity. As a result, BESSs have been installed at certain substations to decongest the network, minimise power losses and improve power system stability. In Publication IV, case studies for the years 2022 and 2030 were simulated, and the results demonstrated, in detail, that BESS can reduce the currents below the limits of current-carrying capacity of concerned transmission lines. With the developed algorithm, the simulation results validated that appropriate sizing and allocation of BESS for any operating harbour grid planning for integrating RESs can be achieved.

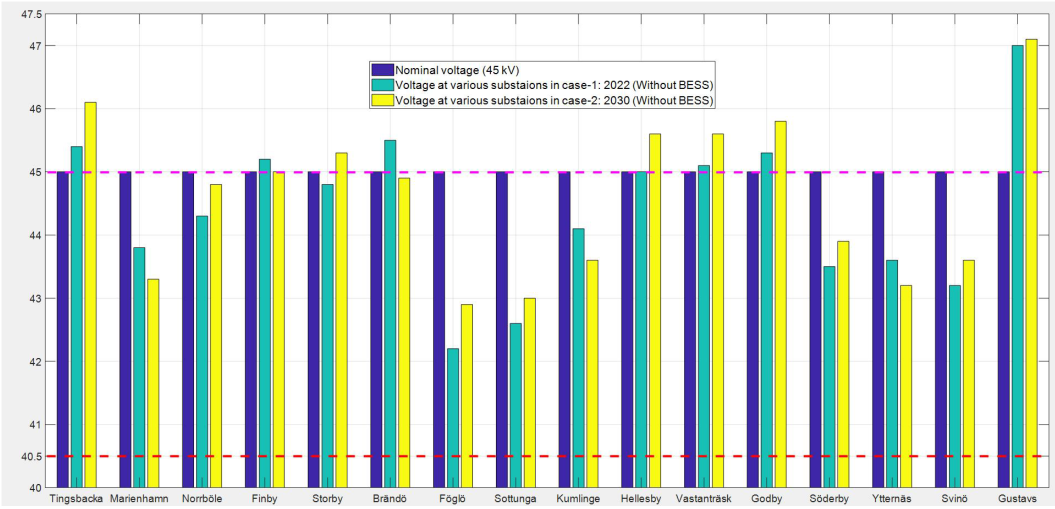


Figure 22. Nominal and operating voltages at the substations in base case (Publication IV)

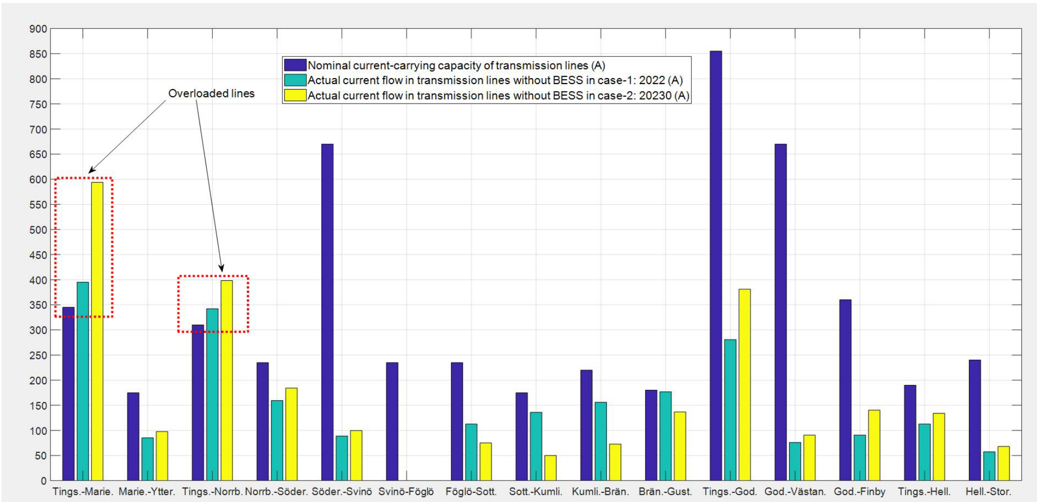


Figure 23. Nominal and actual current flow in transmission lines in the base case study (Publication IV)

5.5 Summary of the chapter

The findings of this chapter indicate that weak electrical grids with several medium-sized or small harbour regions require greater power and energy capacity to accommodate the increased power demands of modern electric and hybrid ships, ferries and other electrical loads at harbours. The higher power requirements especially due to the FCSs in harbours can be accomplished by either additional power supplied to harbour grids from main grids or locally generated power from RESs or BESSs. The power system in the Åland Islands has a substantial capacity for generating electricity locally from RESs, and it is also the corresponding authorities' plan to integrate a certain proportion of wind and PV power in 2022 and 2030. The increasing penetration of intermittent RESs results in power fluctuations and necessitates significant expenditures in improving the capacity of the power systems in the Åland Islands. Therefore, it is essential to design the appropriate size and location of BESS to allow weak grids to cope with the aforementioned load demands. Modern lithium-ion BESSs operate as flexible energy sources by handling short-term power fluctuations. They store energy during off-peak hours, enhance power quality and power system stability. This enables the power systems to reduce peak loads; hence, it increases voltage stability throughout the network and optimises the size and capital cost of passive components, such as transformers, transmission lines and electrical equipment.

The detailed simulation results of the power system Åland Islands are presented in Publication IV, which demonstrates that appropriately sizing BESSs and allocating them at the appropriate substations have several advantages. It obviates transmission line expansion and new equipment installation, such as transformers and protective devices at different substations and lowers peak load demand and certain current flowing transmissions. Publication IV also examines the technical benefits of appropriate BESS sizing and allocation in harbour grids for the Åland Islands power system. Nevertheless, economic assessment of the cost savings of transformers and other equipment due to the delaying of expanding power capacity compared to the net cost of BESS was beyond the scope of this study.

It has been observed that meshed networks minimise the size and expense of BESSs when compared to already operational radial networks. In addition, the meshed network can change the operational perspective by enhancing the power quality and reliability of harbour grid in the Åland Islands. Conversely, the meshed networks are confronted by new challenges, such as an increase in network complexity and the need for more advanced protection schemes.

6 SMART CONTROL AND REAL-TIME TESTING OF BATTERY ENERGY STORAGE SYSTEM FOR HARBOUR GRIDS

This chapter is based on three publications, namely: Publication V, VI and VII. The main objective of the chapter is to develop a smart control algorithm to be employed by harbour-side BESC for a case study of the Vaasa harbour grid test system. This chapter demonstrates one of the main contributions of the dissertation by implementing a smart control algorithm that charges and discharges the harbour-side BESS to shave peak-load demand, it tests the developed control algorithm with real-time SIL as well as HIL tests. In Publication V, a control algorithm for harbour-side BESS is developed in MATLAB/Simulink, which smartly charges and discharges the BESS through bi-directional DC/DC converter and shaves the peak-load demands. Publication VI is the extension of the Publication V, and it first modifies the previously developed MATLAB/Simulink model to make it run on RT-LAB software platform, and then it includes an analysis of the performance of harbour-side BESC in OPAL-RT real-time simulation. In Publication VI, harbour-side BESC is implemented with the IEC61850 communication protocol, and the functionality of the controller is validated in real-time simulation with the concept of SIL by publishing and subscribing GOOSE messages through IEC61850-based standard communication. Publication VII is further extension of Publication VI, which configures and implements harbour-side BESC in a field-programmable gate array (FPGA) based external controller that is interfaced with the OPAL-RT real-time simulator, by employing IEC61850 communication protocol and GOOSE messages. Thus, the main objective of the Publication VII aims to test the harbour-side BESC with the concept of HIL. The detailed explanation, discussion and the results are presented in corresponding research publications. However, this chapter summarises the main contributions of these research publications, and addresses the following research question:

RQ4: How to develop, test, and validate the performance of harbour-side BESC to cope with peak-load power demands with an appropriate control algorithm?

6.1 Smart control of harbour area smart grids

High power requirements at seaports for modern vessels facilitating OPS poses a great challenge of ensuring power availability, typically from the utility grid (Fang et al., 2020) (Acciaro et al., 2014). OPS can account for a significant amount of the overall power consumption of the seaport, and it accounts for several times greater than the total power consumption of terminals. Therefore, it is vital for port administrators to comprehensively understand the power and energy consumption of the seaport profile prior to developing OPS facilities for the vessels (Acciaro et al., 2014). It is important to determine the power capacity of the seaport substation as well as the power capacity of the surrounding area where the seaport is connected with the utility grid. That is due to existing power grids connecting seaport substation may be already limited to power capacity. Therefore, it is worth identifying first the improvements that might be needed for any power grid (J. Prousalidis et al., 2014). This stimulates the integration of different types of RESs into seaport grids (Acciaro et al., 2014). Using suitable techniques, the seaport microgrid can control these multiple RESs and supply OPS efficiently to the modern electric and hybrid vessels berthed at seaports. The application of ESSs in power grids can improve power quality, reliability and flexibility in operation. In this regard, extra electricity can be stored when the price and demand of electricity are low, and the stored energy will be consumed when the price and demand of electricity are high (Chang, 2017).

The key to achieving a sustainable seaport is to balance load demand with the appropriate energy management measures (Hein, Xu, Gary, et al., 2021). Seaports have also to focus on sustainability, which requires the seaport authorities to monitor and coordinate power and energy demands inside the port (Acciaro et al., 2014). The energy supply from RESs is volatile; therefore, and the smart energy management systems in forms of smart grids and microgrids is required to balance power supply and demand in an intelligent way. Smart control can be a suitable solution for smart energy management, and it can be defined as a control system, which can process information data using two-way communication functions. In addition, it also can convert digital data into the physical process and manipulate the output by interchanging some physical states of the system (Zhong, 2011). The electric power demand of commercial ports is predominantly flexible (Gennitsaris & Kanellos, 2019). Therefore, an energy management system that incorporates a well-established management plan for seaports should accurately monitor and estimate the consumption of energy in advance before they implement appropriate energy management systems (Iris & Lam, 2019). Along with the application of RESs, port authorities can enhance energy management by controlling and managing power generation and energy consumption (Acciaro et al., 2014). By employing RESs at seaports, the local power generation becomes indispensable in coping with the growing power demands, but the presence of local power generation in seaports should be controlled to balance power demand and supply (Giuseppe Parise et al., 2016).

The work presented by Heinet al. (2021) proposes a robust method that optimises the day-ahead operational schedule, which is achieved by coordinating seaport microgrids as a grid-connected energy hub. That energy hub integrates uncertain output of RESs and load demand of OPS schedules. The real-time distributed demand response system and power management techniques employing multi-agent systems are proposed by Gennitsaris & Kanellos (2019) and Kanellos et al. (2019). Suitably controlling the power demands of seaport reefer containers and OPS also ensures the reduction in ship emissions, operational cost and power fluctuations caused by local wind parks. Acciaro et al. (2014) demonstrate that active energy management techniques employed to coordinate power generation, the application of RESs and energy in the two European ports Hamburg and Genoa, can improve efficiency and contribute in developing seaport revenue sources. The power management system of the seaport proposed by Kanellos et al. (2019) can ensure storage of huge amount of energy when electricity price is low, and reduction in loading on power grids during peak-load demand. However, limited research work has been conducted that analyses optimal power management in large ports (Kanellos et al., 2019) and compares peak shaving methods in seaports by employing simulation tools (Iris & Lam, 2019).

Despite the fact that the current research is progressing towards optimal control and power management strategies for harbour grids, no previous study has yet developed, tested and validated a harbour-side BESC by charging and discharging of BESS for harbour grids. In this dissertation, Publication V designs and implements BESS for the Vaasa harbour grid system using actual load profile data from OPS. The BESS is a viable option for meeting the increasing power demands at seaports without expanding the power system infrastructure. The performance of the harbour-side BESC was further evaluated by a real-time SIL and HIL tests using IEC61850 GOOSE communication in Publication VI and VII, respectively. The applied approach in this dissertation is a cost-effective way to test the performance of harbour-side BESC, and it is a practical way to charge and discharge BESS when the power supply in a harbour is higher and lower than load demands.

6.2 Modelling and Simulation of Vaasa harbour grid test system

This Section presents the simulation model developed in Publication V for the Vaasa harbour grid. In which, it employs real data obtained from the local distribution system operator Vaasan Sähköverkko and harbour operator Kvarken port of Vaasa. Following the presentation of a detailed single-line diagram of the

Vaasa harbour grid topology, a MATLAB/Simulink model for the Vaasa harbour grid was developed.

6.2.1 Vaasa harbour grid topology

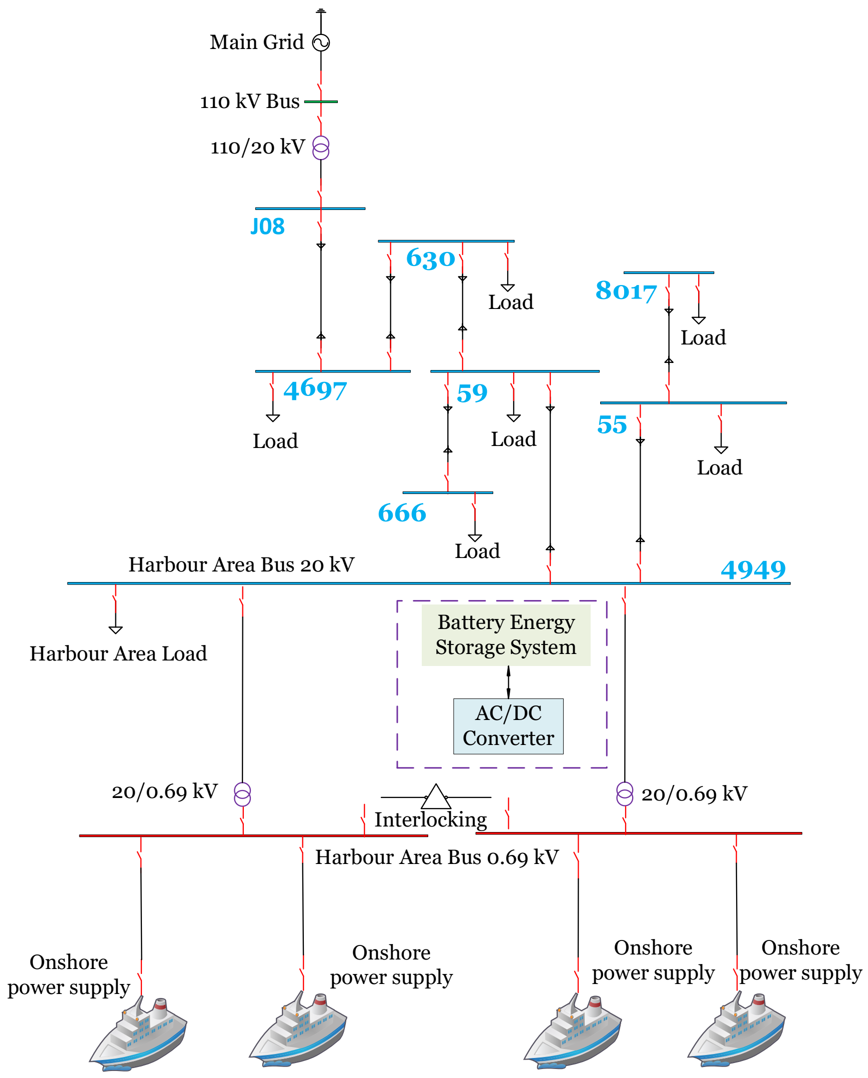


Figure 24. Feeder topology of Vaasa harbour (Publication V)

The detailed feeder topology of Vaasa harbour, where power is supplied by the Vaasa electric supply, is depicted in Figure 24. Through a primary transformer of 110/20 kV, the transmission grid supplies power to the J08 medium voltage (MV) main feeder, which then supplies power to several secondary substations. Those secondary substations include: 4697, 630, 666, 59, 55 and 8017. The new secondary substation 4949 was under development when data was collected in

2020; and it was supposed to enable OPS to the new hybrid electric ferry. The ferry considered for OPS was expected to have the maximum power demand of 2 MW; and the duration of OPS was dependent on the schedules of ferries staying at Vaasa harbour. As illustrated in Figure 24, there are four connection points of docking, where the ferry can connect to the quay, and an interlocking switch is positioned to allow for a variety of docking along with the integration of a BESS.

6.2.2 Simulation model of Vaasa harbour grid topology

The single-line diagram of Figure 24 has been modelled in MATLAB/Simulink, and the model incorporates actual data received for each component, including transformers, conductors (cables), and hourly load profiles of each secondary substation. The new connection at secondary substation 4949 for the Vaasa harbour grid will supply OPS to the new ferry, which will have a fixed arrival and departure schedule at seaports. Considering the new ferry schedule, the OPS load profile at a node (4949) has been calculated, and its data has been incorporated into the MATLAB/Simulink model. There are times when the peak-load demand is significantly high and cannot be sufficiently supplied by the power capacities of the MV feeder and power transformers. To reduce peak-load demand, a BESS of the appropriate size is designed to charge during off-peak demand and discharge during peak demand. According to the amount of power needed, the BESS is charged or discharged using a bi-directional AC/DC converter connected between an AC bus of 0.69 kV and a BESS. Therefore, this methodology proposes to restrict the peak load demand within the power capacity limits of the main grid by controlling charge, discharge and idle mode of operation harbour-side BESS. The details of the aforementioned control algorithm are discussed in the following section.

6.3 The proposed control algorithm for charging and discharging BESS in harbour area smart grids

OPS load for new incoming ferries and their schedules of docking at seaports determine the peak-load requirements of harbour grids. Publication V aims to develop a control algorithm for charging and discharging cycle of the BESS for the Vaasa harbour grid in order to economically meet peak-load demand and prevent any extra burden on the existing power infrastructure, such as power transformers, power cables and, etc. Initially, the developed model is simulated in MATLAB/Simulink without BESS. Then it indicates that the peak-load demand of the harbour exceeds the capacity of the existing electrical infrastructure, namely the transformers and cables. The mismatch between maximum load demand and nominal equipment normal ratings is a critical factor in designing a suitable size of BESS. Following that, the daily, weekly, monthly, and yearly energy demands of the Vaasa harbour grid are computed in order to define the charge and discharge cycle of the BESS. The energy demand varies at different times of the year depending on the schedule of the ferries requiring OPS at Vaasa harbour. The charge and discharge cycle of the BESS is thus determined by the energy consumption by ferries requiring OPS at Vaasa harbour. The size of the BESS and the charging or discharging cycle are selected in such a way that avoids the need to upgrade the MV feeder and satisfies peak-load demands without violating voltage limits of the HVSC standard (IEC/ISO/IEEE, 2019).

The following equations are used to calculate the power flow through charging and discharging of the BESS:

$$P_{battery} = P_D - P_G \quad (1)$$

$$P_D = P_{harbour} + P_{OPS} \quad (2)$$

$$\text{Constraint: } P_G = 2.5 \text{ MW} \quad (3)$$

Where $P_{battery}$ is power absorbed and supplied by the BESS during charging and discharging, respectively; P_D is the total power demand at harbour; $P_{harbour}$ is the harbour load; and P_{OPS} is the OPS. P_G is the maximum power available from the grid. When P_D is greater than P_G, BESS is in the discharging mode. When P_G is greater than P_D, BESS is in the charging mode provided that *SOC* is within the specified limits. Otherwise, the BESS shall remain in the idle mode of operation. The energy storage capacity for the BESS has been designed with the following parameter constraints:

$$20\% \leq SOC \geq 100\% \quad (4)$$

$$SOC \leq 0.2C \quad (5)$$

Figure 25 depicts this proposed control algorithm methodology of energy management. This demonstrates that the BESS is charged to a *SOC* of between 20 % and 100% whenever the power demand is lower than the grid power capacity, and it is discharged whenever the power demand is higher than the grid power capacity. It is advisable that LIBs not be discharged beyond 80% depth of discharge. Therefore, in all other instances, the BESS is in the idle mode. The BESS has been sized so that it is constantly being charged or discharged. Through this way, it avoids idle mode of operation, especially when the power demand exceeds the amount of power supply by the grid.

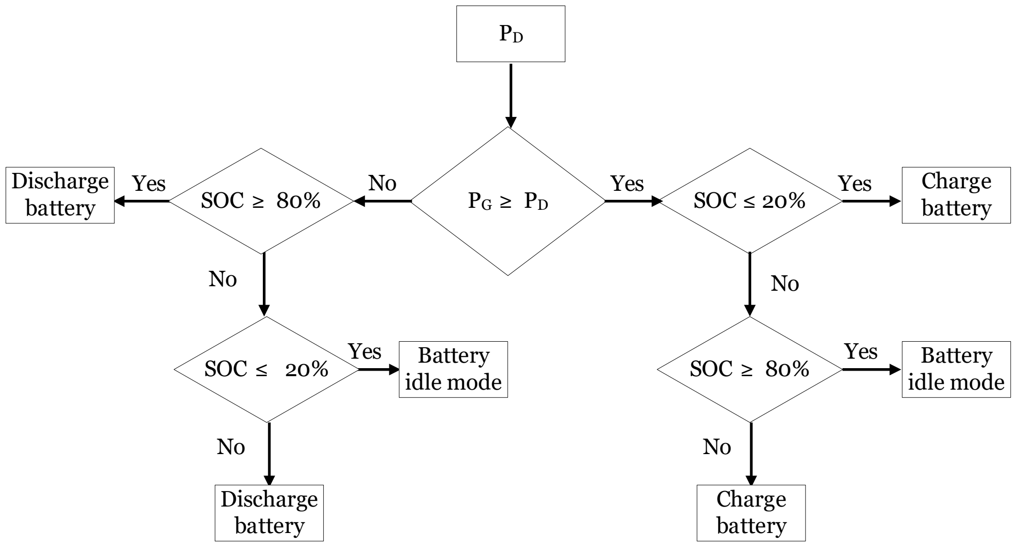


Figure 25. Control algorithm of an energy management system (Publication-V)

6.4 Design and validation of the proposed harbour-side BESS controller in real-time simulation

Power and communication systems were typically designed and validated separately in the past, but modern energy systems are evaluated and tested simultaneously. Along with this trend, real-time simulation has received a lot of attention in the past few years for testing and validating equipment and algorithms in a realistic environment (Benigni et al., 2020). Conventional simulation software tools do not have the possibility to interact with physical components, as in the case of real-time simulation (Memon & Kauhaniemi, 2021). Therefore, the control algorithm developed in MATLAB/Simulink in Publication V has been further modified in Publication VI and Publication VII for validating and testing it in OPAL-RT real-time simulator with SIL and HIL test respectively. The following subsections describe the details of the design, validation and implementation of harbour-side BESC with the IEC61850 standard based GOOSE communication.

6.4.1 Design and validation of harbour-side battery energy storage system controller with IEC61850 based GOOSE messages

This section is from Publication VI, which explains how to employ IEC61850 communication protocol and the GOOSE messages with publishing and subscribing methodology. It proposes harbour-side BESC and tests it with the concept of SIL. The detailed methodology and results are explained also in

Publication VI. The GOOSE publisher and subscriber blocks are developed to exchange information to and from the proposed harbour-side BESC. The GOOSE messages control the status of harbour-side BESC for charging, discharging or operating in idle mode whenever required. This requires the development of the IEC61850 substation configuration description language (SCL) file, and it must be adapted to the software testing platform. The SCL file generates an object-oriented data model for harbour-side BESC, which contains logical nodes (LNs), data objects (DOs), and data attributes (DAs). The LNs, DOs and DAs are used to handle and process measurements data from the field. In this study, the data is received from the simulation model, which has been modelled and simulated in OPAL-RT real-time simulator. Furthermore, GOOSE control blocks (GCBs) were developed and configured by building GOOSE data sets. The DA data set should be associated with the publishing GOOSE message for harbour-side BESC. The configuration of the GCB is then finalised with GCB parameters, such as GOOSE publishing MAC address, GOOSE subscribing MAC address, GOOSE ID and GOOSE configuration revisions, etc. The details of the SCL file code are further explained in Publication VI.

The control functions of harbour-side BESC such as charging, discharging, and idle mode have been developed in C language to comply with SIL test simulations requirements that run with the OPAL-RT eMEGASIM simulator. Thus, the harbour-side BESC can select the operation mode of harbour-side BESS by subscribing to the GOOSE message sent from harbour-side BESC, which uses the measurements from the grid model. After receiving the subscribed GOOSE message with the measurements, harbour-side BESC extracts them and then it runs the control function. Now, the control function outputs the reference signal (0, 1, or -1) depending on power demand (P_D) and *SOC*, as illustrated in Figure 26. The referenced signal controls the operation of BESS to be switched among charge, discharge or idle mode of operations.

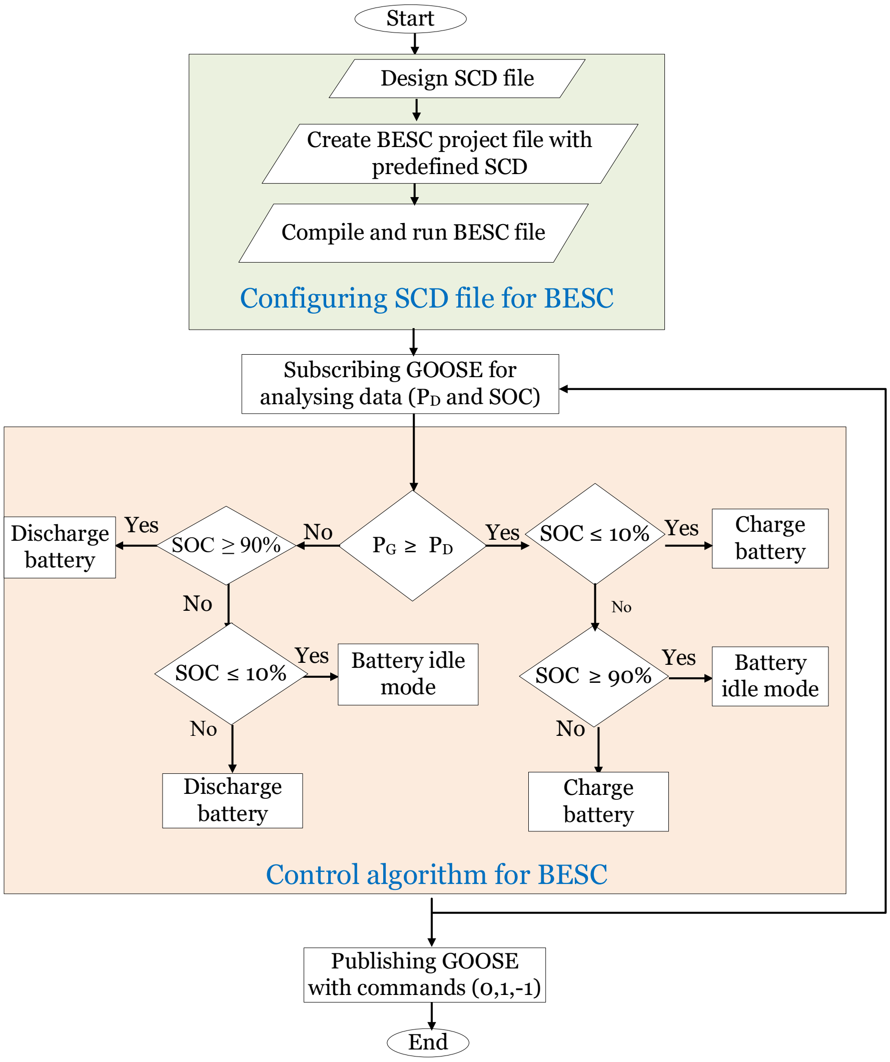


Figure 26. BESC algorithm using IEC61850 GOOSE message (PublicationVI)

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

This section is from Publication VII, which explains in details the procedure of developing HIL testbed, and it compares offline and HIL test results. In Publication VII, harbour-side BESC is implemented on a physical device called FPGA card, with GOOSE publisher and subscriber blocks configured to send and receive GOOSE messages from OPAL-RT simulator. To implement HIL testbed, the functionality of harbour-side BESC is developed with the following steps:

- The bi-directional communication links for harbour-side BESC were developed in accordance with IEC61850 standards.

- A data object model is designed and developed based on IEC61850 standard specifications.

- An intelligent harbour-side BESC algorithm is developed on the basis of Boolean logic, which is then implemented on FPGA controller using C code in a LINUX environment.

The HIL is developed in closed loop simulation setup, where GOOSE publisher block is added for enabling to encapsulate the measured values of P_D, and *SOC* from the real-time simulator (OPAL-OP5600) test model to harbour-side BESC. The harbour-side BESC is developed to have the capability to subscribe to GOOSE messages coming from the model through a real-physical communication network. In order to accomplish the GOOSE communication setup, harbour-side BESC has to be configured according to the GOOSE subscription parameters (MAC address, GOOSE IED, etc.) so that they match the GOOSE publishing parameters in the simulation model. In order to publish and subscribe the GOOSE message, the IEC61850 GOOSE publisher and subscriber code blocks are designed and configured from the OPAL-RT test model for implementing harbour-side BESC on the FPGA board. Based on the received values of PD and SOC sent through GOOSE, the proposed harbour-side BESC with the control algorithm calculates the mismatched power. Figure 27 shows the real-time experimental setup, which was developed in the FREESI lab at the University of Vaasa.

The control algorithm of harbour-side BESC is initially developed as Simulink blocks, which must be converted to C code for implementing on the FPGA LINUX environment. The control algorithm outputs the reference signal. On the basis of the referenced signal, the BESS is switched among charge, discharge, and idle mode of operations as follows: (Output=0=>Idle, output= +value=> discharge, or output= −value=> charge) based on the values of PG, PD and SOC. This reference signal is encapsulated in another GOOSE message and transmitted from the harbour-side BESC to the real-time simulator through an Ethernet network. Inside the real-time simulator model, GOOSE subscriber blocks (both GOOSE subscriber old version block based on MATLAB/SIMULINK and new version block based on OPAL-RT IEC 61850 driver for comparing the results) were configured to subscribe to the GOOSE message containing the reference value from harbour-side BESC. After a successful subscription, the reference value must now be extracted from the received GOOSE signals and provided to the real-time model running the inside the simulator for controlling the operation of BESS.

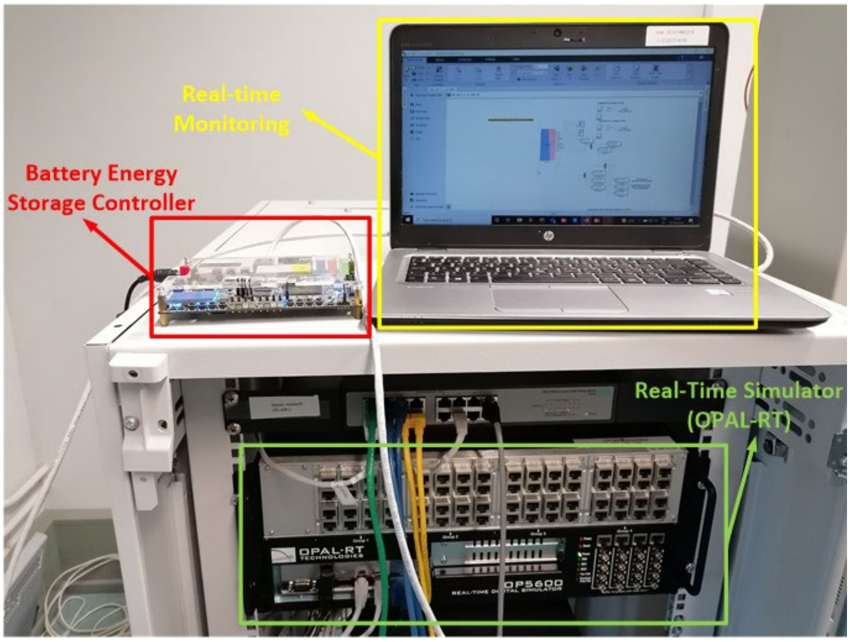


Figure 27. HIL experimental setup for the BESC implemented in the FPGA board- Publication VII

6.5 Simulation results

This section presents some of the results from Publication V, VI and VII to show that the performance of the proposed control algorithm and comparison based on the results of offline simulations with real-time simulations.

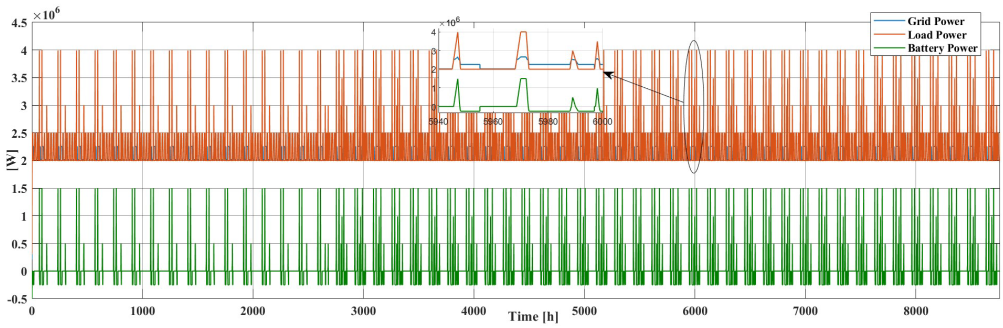


Figure 28. Grid power, load power and battery power (Publication V)

Figure 28 shows the result from Publication V, which shows grid power, battery power, and load power. The maximum power capacity of Vaasa harbour is limited and taken as 2.5 MW, whereas the maximum load demand at Vaasa harbour is 4 MW at some times of the year depending on the schedule of vessels requiring

OPS. The extra power is therefore supplied by the harbour-side BESS according to the proposed control algorithm in Publication V in such a way that harbour-side BESS is in discharge mode when the load demand exceeds the grid power limit and vice versa; provided that the SOC is within the specified limits (20%≤SOC≥80%). Otherwise, the harbour-side BESS will be in idle mode of operations to avoid deep discharging and overcharge issues. In Publication VI, the same control algorithm was employed with some minor changes in SOC limits (10%≤SOC≥90%) to observe the performance close to the depth of discharge and near full charge. In addition to this minor change, harbour-side BESC was designed and created with the SCL and GOOSE messages were used applying the IEC61850 standard. This implementation also provided almost similar results in real-time simulation as that presented in Publication V.

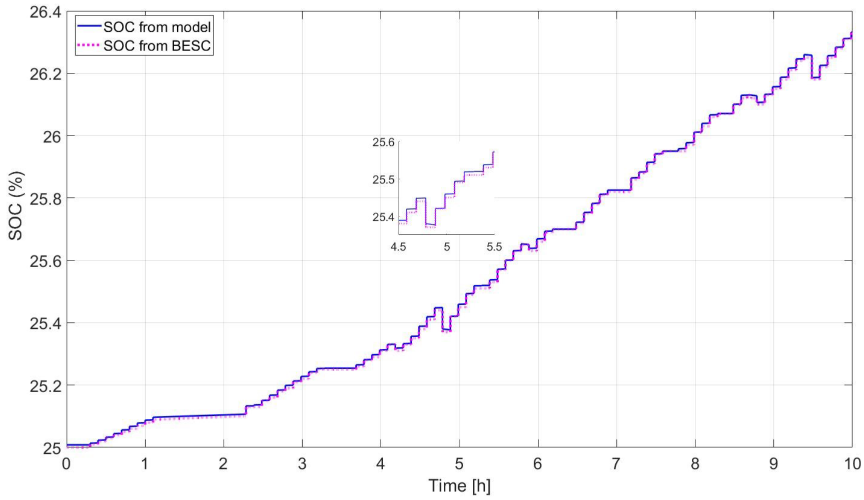


Figure 29. Comparison of SOC=25% from BESC and model (Publication VII)

In Publication VII, harbour-side BESC is implemented on an external device FPGA card, with GOOSE publisher and subscriber blocks configured to send and receive GOOSE messages from OPAL-RT simulator for performing the HIL test. Though the main results of the HIL test are in Publication VII, only some results are shown to observe the performance of harbour-side BESC under the HIL test. Figure 29 shows the comparison of the results of SOC at 25% with offline simulation results of MATLAB/Simulink versus real-time simulation results obtained through the GOOSE subscriber and Publisher methodology. The analysis indicates that offline simulation results are almost the same as that of real-time simulation results obtained through the HIL test, and the only difference is in time delay of the control signal of HIL test results due to communication latency.

The simulation results validate that harbour-side BESS can be developed with the proposed control algorithm while considering harbour grid data of power supply from the main grid, and the power required for modern vessels for OPS and battery-charging systems. Moreover, the performance of harbour-side BESS can be validated with SIL and HIL tests in real-time simulation by applying IEC61850 GOOSE standard communication.

6.6 Summary of the chapter

The growing power demands at harbour grids is mainly because of OPS, and battery-charging stations required for modern electric ships. This may cause an increase in peak-load demands and, subsequently, require immediate actions to be taken to raise the power capacity of power systems. Alternatively, this may lead to the implementation on local power balancing at the harbour grid through integrating RESs and BESS. Therefore, the application of smart energy management techniques would be required to optimally coordinate multiple energy resources to gain technical as well as economic benefits. The BESS can enable more flexible, reliable and resilient operation of harbour girds. However, it is necessary to design, test, and validate harbour-side BESC while managing electric power supply and consumption according to the needs of harbour operations and availability of RESs.

In this dissertation, harbour-side BESS is first designed based on the load profile of OPS, and the schedule of vessels staying at harbours. Then, an appropriate control algorithm is developed for harbour-side BESC, which can shave peak-load demands. The developed control algorithm is implemented in a case study of the Vaasa harbour grid test system, where it balances the power mismatch of demand and supply by charging and discharging the BESS. The developed control algorithm is then validated with SIL and HIL tests, which have been conducted in real-time simulation with IEC61850 GOOSE standard communication. The results of these tests further validate the performance of harbour-side BESC, and it has been observed that the real-time simulations are following the offline simulation results with some communication delay known as latency.

It has been concluded by implementing the proposed harbour-side BESC in a case study of the Vaasa harbour grid test that it is an appropriate way to design, test, and validate the performance of harbour-side BESC to achieve a power balance for harbour grids. Moreover, it is a reliable and cost-effective way to validate the performance of the control algorithm in real-time simulation with HIL test. The economic analysis of investment on BESS based on payback time in the harbour grid to cope with the growing peak-power demand can be a focus of future research work for the harbour grid.

7 CONCLUSIONS

This chapter starts with a discussion, points out the key contributions and summarises the research work of the dissertation. In the end, it introduces some pathways for future research.

7.1 Discussion

This study has discovered that serious actions being taken by the IMO, EU-Directives, and Paris agreement are the main drivers in revolutionising maritime transport by phasing out fossil fuels from maritime transport and enabling the applications of RESs and advanced technologies for maritime transport. This shifts the paradigm from favouring conventional marine vessels and harbour grids to modern electric and hybrid vessels and HASG by placing high standards on environmentally friendly technologies, such as alternative green fuels, OPS, and multiple ESSs especially BESS. Thus, the modern vessels and HASG, unlike conventional vessels and seaports, do not require only logistic infrastructure, but they also need to implement smart power control and energy management techniques and advanced technologies, including communications, information technologies, and real-time testing and validation of the power controllers, digitalisation, artificial intelligence, big data analysis and the IoTs.

Traditionally, shipboard power systems are mainly dependent on non-renewable energy resources, and negligible flexibility is available to obtain power supply from harbour grids. The above discussion recognises that maritime transport has to shift from conventional vessels that operate on fossil-fuel based power generation towards modern vessels that operate on power generation from green fuels and RESs along with integrated energy systems. Therefore, this thesis proposes the technological progression of marine vessels and harbour grids, which would require a shift in two phases. During phase-I (near-future phase), conventional vessels have started to shift to hybrid shipboard power generation utilising bio-fuels, hydrogen fuel and renewable. A small percentage of non-renewable sources together with a little flexibility of power are being supplied from harbour grids. However, during phase-II (far-future phase), shipboard power generation would mostly exploit more RESs integrated with BESS along with more flexibility of power being supplied from harbour grids, which will also have advanced power generation solutions having power-to-x ESSs.

In order to strictly follow the emission reduction rules, marine vessels staying at harbours have to employ either green fuels for power generation or shut down auxiliary diesel engines and employ OPS from harbour grids. OPS from harbour grids can be deemed as flexibility being provided by harbour grids, and it can serve multiple purposes, such as heating, cooling loading, unloading, lighting, ventilation and also battery-charging for electric or hybrid vessels. Indeed, OPS has many advantages such as a reduction in huge amount of toxic emissions, which can pollute air and threatens the health of inhabitants and living beings nearby harbours. However, modern electric and hybrid vessels OPS and battery-charging systems would require a relatively large amount of power, which may cause serious technical challenges for harbour grids.

To deal with these challenges, the integration of large-scale RESs connected with utility grids is indispensable, but the output power from only RESs is stochastic by nature. Therefore, designing a suitable size of BESS in harbour grids is essentially required to support weak harbour grids, avoid the expansion of power systems, balance power supply and demands, and improve power system stability, reliability and flexibility. The harbour-side BESS can also be used for an energy management systems to smartly control charging or discharging of batteries, and obtain energy arbitrage and peak shaving solutions. This requires appropriate control algorithms for harbour-side BESC, whose performances need to be tested and validated before implementing in an actual system. For that, real-time simulation offers a suitable and cost-effective ways to test and validate the performance of harbour-side BESC.

7.2 Contribution

This section first presents several noteworthy contributions of the dissertation, which can be broadly categorised into four main contributions, as described in Chapter 3 to 6. Moreover, this section later also presents brief answers to the research questions raised in the first chapter of the dissertation.

Chapter 3 focuses on the first main contribution, which covers the literature review and introduces a novel concept of HASG. Publication I and II discuss this contribution in depth. Publication II explores state-of-the-art and foreseeable future marine solutions for modern vessels and harbour grids. Publication II has provided a comprehensive review of technical aspects, existing standards, practices and key challenges in designing and modelling harbour grids supporting OPS. In Publication I, the HASG model was developed and simulated in PSCAD software, which mainly supports OPS and battery-charging systems for modern electric and hybrid vessels. The detailed results from the simulated model in Publication I show that they are within the HVSC standard limitations, and the model performs well under steady state as well as the transient mode of operation.

Moreover, based on the developed model in Publication I, two more modified versions of the model were also presented in Publication II, which were basically designed for the same purpose with smaller electrical equipment to save space and capital cost. One of the modified version of the model proposes a new concept of replacing a frequency converter with harbour –side BESS by employing AC/DC and DC/AC converters in such a way that harbour –side BESS is charged during off-peak load demand and can serve as an alternative of frequency converter.

Chapter 4 demonstrates the second main contribution of the dissertation, and it is based on Publication III. In Publication I and II, several models for harbour grids were already developed to support OPS and battery-charging systems. However, in order to progress the previous research, Publication III has extensively investigated various novel harbour grid models that support OPS and battery-charging systems for modern electric and hybrid vessels. These models mainly focus on presenting multiple battery-charging configurations, which are then compared on the basis of technical and practical implementation perspectives. Moreover, slow and fast-charging of battery-charging configurations were developed in PSCAD software. The results are presented in Publication III, which illustrate that these models accomplish the desired objectives to charge the batteries within 10 and 2 hours for slow- and fast-battery-charging systems, respectively. It was concluded from the literature review that it was the first attempt to systematically review and technically analyse multiple battery-charging configurations, which could serve as a basis for future business for ship owners, port terminal administrators and policy makers.

Chapter 5 covers the third main contribution of the dissertation, which is presented in Publication IV. Modern harbour grids require a large amount of power when facilitating modern vessels with OPS and battery-charging infrastructure. Typically, harbour grids are not designed to cope with these heavy demands, therefore local power generations from RESs at seaports would be a better option as compared to extend the capacity of power systems. However, RESs generate fluctuating power, and should be integrated with ESSs, especially BESS. Publication IV for the first attempted to design BESS for any operating harbour grids planning for integrating a huge amount of RESs. The algorithm was developed in MATLAB/Simulink, which by incorporating inputs from the corresponding PSCAD model computed the appropriate size and location of BESS. The developed algorithm was then applied in a real test system of a harbour grid in the Åland Islands, and two case studies were analysed with the integration of large-scale RESs. The results show that proper sizing and allocation of BESS can mitigate line congestion, avoid peak load demands and ultimately defer immediate capital cost by avoiding power system expansions.

Chapter 6 presents the fourth and final main contribution of the dissertation, which is covered in three publications: Publication V, VI and VII. This chapter implements a smart control algorithm that is based on a practical approach to charge and discharge the harbour-side BESS. The developed control algorithm was tested in a real-time simulation with SIL and HIL tests. In Publication V, a control algorithm was developed in MATLAB/Simulink for harbour-side BESS, which smartly charges and discharges the BESS. Publication VI expounds from Publication V by modifying the previously developed model and analysed the performance of harbour-side BESC in OPAL-RT real-time simulation. Also, harbour-side BESC was implemented with the IEC61850 communication protocol, and the functionality of the controller was validated in real-time simulation according to SIL by publishing and subscribing GOOSE messages. Publication VII is further extension of Publication VI by configuring and implementing harbour-side BESC on a FPGA-based external controller interfaced with the OPAL-RT real-time simulator by employing the IEC61850 communication protocol and GOOSE messages. Thus, the main objective of the Publication VII is to test the harbour-side BESC with the concept of HIL. The detailed explanation, discussion and the results are presented in the corresponding research publications. The literature review reveals that this is one of the novel contributions of this dissertation, which develops the harbour-side BESC and tests its performance in real-time simulation with SIL and HIL tests. The results validate that the developed and tested harbour-side BESC can smartly shave peak-load demands of harbour grids by charging and discharging BESS.

In addition to the above detailed description of the contributions, here are the following persuasive answers to the research questions raised in the first chapter of the dissertation along with these research questions:

RQ1: What are technical design aspects, standards and barriers in designing HASG supporting OPS and battery-charging infrastructure?

The design of a harbour grid is a challenging task when considering environmental, technical, safety and protection issues. It is also difficult to adhere to standard regulations and keep up with continuous development in the field of marine technology. The IMO, EU-Directives, and some other well-known organisations have set the limits and targets to reduce emissions and increase energy efficiency for marine transportation. This prompts relevant stakeholders to employ more electrification by utilising RESs, OPS and battery-charging infrastructure for operating modern harbour grids.

Besides coping with large amount of power and energy requirements due to electric and hybrid vessels, the modern harbour grids have to be designed and operated in accordance with the standard for HVSC systems. In order to meet the HVSC standard requirements, few technical requirements are mentioned as follows: the OPS should be provided with a dedicated high voltage shore supply with galvanic isolation from other connected ships and consumers; it should supply power with 6.6 kV or 11 kV to decrease the number and size of cable in comparison with the low voltage. Other than this, operating voltage should not exceed and drop by 6% and 3.5%, respectively. Operating frequency should not exceed ±5% during no-load to nominal load condition, and total harmonic distortion of voltage should not be above 5% limits.

The main barriers in widespread implementation of OPS are from economical perspectives such as who should invest (port owners, ship owners, utilities of power supplies, etc.), technical viewpoints such as high cost will be for the initial retrofit of vessels to comply with the IMO requirements. There is also the lack of interest from the local or regional governments and world-wide associations.

RQ2: What could be different types of battery-charging configurations of HASG and how to compare them based on specific vessel and harbour grid requirements?

There could be several possibilities of battery-charging configurations to support modern electric and hybrid vessels employing BESS as a main source of power supply. However, each design has its technical limitations from the perspective of practical implementation. There are multiple types of vessels that have different power demands, the schedule of staying at harbours, voltage and frequency levels. Likewise, each harbour grid has its limits of power capacity, availability of power infrastructure and space, and the possibility to support AC, DC, or both (AC and DC) types of grid; therefore, each harbour grid may not be able support different types of vessels for battery-charging systems due to the aforementioned technical issues. Therefore, it is worth deeply analysing multiple battery-charging configurations from technical, environmental, as well as economical perspectives to ascertain which configuration is suitable for a specific case.

RQ3: How to solve the challenging issue of appropriate battery sizing and allocation at different nodes of the distribution system connected with the harbour grid, which deals with growing power demands with the integration of RESs?

The power and energy demands at harbour grids will instantaneously increase in the future when they facilitate modern electric and hybrid vessels with OPS and battery-charging infrastructure. Actually, there is currently sufficient power capacity, but the power requirements of modern vessels will increase the level of demand. One solution is to expand the power capacity of the distribution system and transmission system by installing new lines. However, this may not be viable option due to cost, and the power generation system connected through the transmission and distribution networks to harbour grids may also have limited power capacity. Therefore, the penetration of local power generation from RESs at various nodes of distribution systems connecting harbour grids is one of the appropriate solutions to cope with the growing power demands of harbour grids. However, the fluctuating nature of power generation from RESs necessitates the integration of BESS to smoothen the power required for harbour grids. Therefore, certain algorithms are needed to properly size and locate BESS at various nodes of distribution networks. In this way, congestion in the transmission and distribution networks connecting harbour grids can be avoided, and the additional cost for expanding the power capacity of the distribution network can be deferred.

RQ4: How to develop, test, and validate the performance of harbour-side BESC to cope with peak-load power demands with an appropriate control algorithm?

In order to shave peak-load power demands, harbour-side BESC is required to systematically control the charge and discharge cycle of harbour-side BESS in HASG. This is achieved by first developing a suitable control algorithm and then testing its performance with some standard tests. In the past, power and communication systems were considered separately from design and validation purposes because conventional simulation tools did not have the possibility to interact with physical components. However, real-time simulation tools are capable to analyse the performance of the developed control algorithm with some standard tests, such as SIL and HIL tests, to be performed with some IEC61850 communication protocol. The real-time simulation environment is an appropriate and cost-effective way to evaluate the performance of harbour-side BESC, and the results from these simulations are also acceptable to be implemented for any harbour-side BESC.

7.3 Future work

This dissertation has mainly contributed in designing and controlling some suitable simulation models for HASGs with application of BESS while considering technical challenges. However, this research has opened some questions in the following research areas, which need to be further investigated:

- In the future, more research and development is required for implementing novel control methodologies and advanced technologies in HASG that incorporate RESs with integrated ESS and consist of multiple types of ESSs besides BESS. The power-to-x ESSs for harbour grids have not yet been extensively studied and needs attentions for future research studies while considering business models for HASG with smart energy management plans to buy and sell electricity in the energy market.

- Hybrid microgrid having both AC and DC connections for harbour grids is an interesting research subject for future studies because hybrid microgrids have significantly more potential than conventional AC microgrid for integrating multiple RESs, and they can facilitate the combination of slow- and fast-charging battery-charging configurations while exploiting the advantages of both types. Moreover, harbour grids can be expanded and operated on a modular basis to cope with the specific power requirements of different ships visiting the harbour area simultaneously by applying advanced control techniques.

- Future research on harbour grids can focus on the economic analysis of BESS and other ESSs investment based on payback time in harbours to handle the increasing peak-power demand. The optimal design of the BESS can be determined by employing suitable decision-making models that integrate forecasting methods to anticipate peak load periods.

- Despite the various benefits of using OPS, only a few seaports in the world are currently gaining benefits. Therefore, further research is needed to investigate how to incentivise seaports to employ onshore power technology based on some suitable business models. This can only happen, when all the stakeholders, including ship owners, port administrators, terminal operators, policy makers, researchers, and local governments, participate collectively in creating appropriate business models for promoting it.

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Designing and Analysis of Innovative Solutions for Harbour Area Smart Grid

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***Abstract*—Nowadays, different vessel types are mostly operating on diesel generators employing cheap quality fuel, thus causing many types of air pollutions during a stay at the harbour. Thus, electrification by renewable energy based Distributed Generation (DG) and Battery Energy Storage (BES) onboard as well as on shore side are inevitably the best solution to get pollution free energy. In this regard, this paper proposes an innovative design concept of the Harbour Area Smart Grid (HASG) in such a way that it can not only supply the vessels for cold ironing purpose but also supports the hybrid vessels of future technology. The designed HASG is modelled in PSCAD/EMTDC and the simulation case studies have been carried out to validate the performance of the HASG under steady state and transient state.**

***Index Terms*-- Battery energy storage, Cold ironing, Distributed generation, Harbour grid**

I. Introduction

Nowadays the marine technology plays a very vital role because more than 90 percent of global trade flow is based on seas and oceans [1] [2]. The marine vessels are considered as floating power plants [2] in terms of supplying power to the vessels during travelling as well as during stay at the seaport or harbour area. Currently, most of the vessel types are operating on diesel generators (main and auxiliary) [1]-[3]. The fuel used for the marine application is of cheap quality and it is the main cause of many types of air pollutions [1] [2] [4]. Due to the environmental impact of air pollutions created at harbour area, many ports are restricting the operation of onboard generators while the vessels are berthed [5]. Moreover, there is a great concern about fuel consumption [4], because of the biggest challenges of environmental issues, rising prices of fuels and the depletion of fossil fuels [6] [7]. Besides these problems, there is a technical challenge to design the grid architecture at the harbour area in such a way that it does not only provide the power supply for the cold ironing to get rid of air pollutions but also support the future hybrid vessels. The future hybrid vessels will be employing the BESs as the main source of the power supply by replacing diesel engines or by retrofitting the BESs along with the diesel engines. Thus, they will change the current paradigm of the harbour area grid because these hybrid vessels will not only require the power supply for cold ironing but also for charging the BESs at the harbour area.

The on shore power supply [8]-[12] in the marine application has been implemented recently in some ports of the USA, Canada and the Europe (Germany, Netherlands, Belgium, Norway, Sweden, Finland) [9] [11]. The process of shutting down all the diesel engines of the vessels and supplying the vessels by the shore-side electric network during a stay at the harbour is historically known as cold ironing (shore connection) [9] [13] or shore side power supply [4]. The cold ironing provides an efficient and effective solution to the problems of emissions and pollutions generated at harbours [9] while reducing the production of the toxic particulate matters [12] [14]. Moreover, it has been observed that 46% of the carbon-dioxide emissions are reduced with the local (Spanish) power generation mix as compared to the onboard generation [12]. Thus, the HASG must be designed with the special focus on the application of cold ironing so that the harbours should get rid of the pollutions.

Recently the exemplary concept of All Electric Ship has been given in [15], which is supposed to be the most efficient ship that replaces the conventional mechanical system with electric propulsion. There are some implemented projects in the world such as a hybrid green ship (PV/diesel) [3], in Geoje island, South Korea, which demonstrated a possible retrofit solution including photovoltaic generation and the BES along with diesel engine. There is also an extensive feasibility study about sailboats in Italian harbours [16], where the diesel generators were assumed to be replaced with the BES and Renewable Energy Source (RES) as DG in the vessels. The concept of smart port [16] has been considered as an energy district to improve renewable energy penetration and enhance

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European grid storage capacity by selling the electricity to the market through the national grid. Whereas the concept of wise port [17] mentions the necessity of microgrid at the sea port and assumes the harbour area as a unique territory that should have new business models with its own master energy plan consisting of medium and long term energy storage. These concepts of smart port and wise port focus on feasible and smart management of electricity from a business viewpoint so that electricity at the ports can be exchanged with either between hybrid vessels and port or between the port and national grid on an economic basis. The literature review conducted so far leads to these research questions: How to design and model the HASG in such a way that it can not only support the cold ironing but also the hybrid vessels of future technology? How will this HASG be different as compared to the normal concept of smart grid in the power system?

The objective of this paper is achieved by filling the research gap of designing an innovative smart grid at harbour area in such a way that it copes with the challenges of providing emission free generation for cold ironing as well as supporting the future hybrid vessels while focusing on the above research questions. The rest of the paper is organised as follows. Section II provides an overview of the harbour area smart grid. In this section, three main segments are covered: how emission free generation can be achieved by applying the DGs in the HASG, why the BESs are employed in the HASG and comparison of normal concept of smart grid in the power system and in the harbour area. In Section III, the proposed model of the HASG design is presented along with the current standard requirement of High Voltage Shore Connection (HVSC) for cold ironing. The simulation results are discussed in Section IV, and the conclusion is presented in Section V.

II. HARBOUR AREA SMART GRID

The cold ironing should employ a near zero or emission free technology to provide cleaner power to the docked ships [5]. Thus, the electric generation from renewable sources such as solar and wind turbine (WT) should be employed at harbour area nearby the seaports [9] [14] [17] to have an economical as well as clean energy. The higher penetrations of DG operating in the HASG will not only protect the harbour area from the environmental pollutions but bring many benefits to the terminal operator in terms of saving the cost due to heavy demand charges billed by the utilities [17] and improving reliability and efficiency of power supply [18] [19]. The DG has a relatively low capital cost compared to its central power plants and can reduce losses in the distribution system as well as in the transmission system [20] [21] [22]. The DG units are located near the seaports at harbour area to avoid expansion of the existing network so as to supply power for the purposes of cold ironing to conventional as well as hybrid vessels and for charging system of the BESs at the HASG.

The output power of the DG is uncontrollable because it depends mostly on renewable sources, which are intermittent in nature [23]. Thus, the penetration of DG will raise the concern of unreliable and unsatisfactory operation in the HASG. There are some techniques like probabilistic approach, possibilistic approach, hybrid probabilistic possibilistic approach and information gap decision theory [24] that can be applied on the DG to address the uncertainty in the generation due to variable operational parameters (e.g. the wind and solar irradiation). However, in order to get the full benefit from the DG, the integration of energy storages is viable option to improve reliability and stability of the HASG especially in island mode (when the supply from main grid is unavailable) [15] [23]. The battery technology as an energy storage will play a very important role in the marine application due to a reduction in cost [16], improvement in performance and reliability [15]. The batteries can be used as a system to interchange energy with grid in such a way that energy can be stored in it during time period of low-demand low-generation cost from the grid or from intermittent RES and can be supplied to the grid while there is a high demand high generation cost or when no other generation is available [23]. Since the future hybrid vessel will consist of the battery storage as the main source of power supply during the operation mode, thus will require some charging scenarios at the HASG. In the HASG, the batteries for the hybrid vessels are charged at the harbour area during off-peak time and are replaced with discharged batteries during cold ironing process. The lithium ion battery is ideally suitable for the application where high energy density and high overall efficiency of BESs is required [23], the other characters like cyclic life is 1000, even with deep discharge cycles and moreover it provides the prominent results when combined with wind power and photovoltaics in electricity grid [25].

By combining a smart grid with cold ironing concept a significant reduction in infrastructure; especially in the field of communication and IT equipment can be achieved as compared to the normal concept of smart grid in power system [14]. The port is considered as an industrial load [17] or centralised load and concentrated on limited space whereas in the case of normal smart grid concept in power system the load is geographically dispersed thus requiring more cost on developing an extended communication system with distributed intelligent devices [14]. Moreover, in normal islanded distribution network supplied by the DG, optimal load shedding due to under frequency may be applied on distribution network based on random and fixed load priority [26]. In the case of HASG, the option of load shedding is not possible due to the importance of time schedule of the stay of each vessel at a particular seaport. Therefore, it is important to have instantly as much energy as demanded by hybrid vessels at harbour area. Moreover, the BESs will also play a significant role in island operation of the HASG by managing the power balance by utilizing centralised or decentralised control methods for the BESs [15] [27], so that the uninterrupted operation of the whole system can be ensured.

III. MODELLING HARBOUR AREA SMART

In this section, before modelling the harbour area smart grid, the current standard requirement of high voltage shore connection is presented. Afterwards, the proposed design layout of the HASG is outlined.

A. Current standard requirement

Before the current standard of the HVSC, many ship operators and ports were striving to have an appropriate specification for interconnecting the vessels with the onshore power supply [28]. However, the current standard HVSC as shown in Fig.1 has solved many technical problems and can be adopted as worldwide for cold ironing, i.e. to supply power to the vessels at harbour area with shore supply network.

The HVSC [13] consists of onshore supply and ship's network. On shore side supply, as well as on ship side there are circuit breakers and relays for switching and protection. In between these two networks, there is an interface through circuit breakers, protective relays, control, and communication cables. Moreover, according to the HVSC standard, a shore side transformer must be provided on-shore mainly for two reasons:

- To provide a dedicated High Voltage (HV) shore supply installation with a galvanic isolation of supply from other connected ships and consumers
- To supply high power with 6.6 kV or 11 kV will decrease the number and size of cables used as compared to the low voltage.

B. *Proposed Harbour Area Smart Grid Design/Model*

The proposed single line diagram for the HASG is illustrated in Fig.2, which serves mainly for two purposes; cold ironing and supporting the future hybrid vessels. The cold ironing application is not common yet, but it has been used in some of the ports worldwide as mentioned in Section I. Combining the application of cold ironing with the charging of the batteries for the future hybrid vessels in the harbour area is the novelty of the HASG introduced in this paper.

The proposed HASG consists of photovoltaic as a DG and the BESs at different locations for the sake of reliability and stability of the power supply. The point of common coupling for the HASG with the main grid supply is the harbour area bus of 20 kV, 50 Hz, where the wind turbine from some nearby area is also connected. Thus, the harbour area bus is considered as the main bus of the harbour area from where the power flow towards the HASG can be controlled. The hybrid vessel bus and the frequency converter stations are located nearby the seaports in the harbour area. The frequency converter is used to convert from 20 kV, 50 Hz supply to 20 kV, 60 Hz supply for the vessels operating at 60 Hz for cold ironing. The shore side transformers according to the HVSC standard requirement are connected with hybrid bus and frequency converter station to step down the voltage from 20 kV to 6.6 kV at 50 Hz and 60 Hz respectively. Thus, two dedicated ship buses are used for supplying the vessels at 50 Hz and 60 Hz. The main objectives of the proposed system, as illustrated in the single line diagram can be achieved by supplying the power to the vessels during cold ironing as well as charging the batteries for hybrid vessels. In the case shown in Fig. 2 the batteries are movable and installed in containers which makes them suitable for retrofit applications. The other possible solution is to charge the fixed batteries at the vessels while they are berthed at the harbour. Thus, with this kind of system it is possible to meet the requirement of emission free generation in harbour area.

The proposed system model can provide multiple solutions simultaneously to the problems of greenhouse gas emissions, harmful air pollutions and facilitating the future hybrid vessels at the harbour area. The HASG in this paper enables an emission free solution by the PV and BESs at the harbour area along with shore side supply. The other promising feature of the HASG is to support the future hybrid vessels at the harbour with the charging of the batteries for the hybrid vessels. The batteries can be charged in a container (movable) during off-peak time and replaced with discharged batteries of the hybrid vessels during the process of cold ironing at harbour area. This facility of charging of batteries at the harbour area is a very crucial step towards the rapid

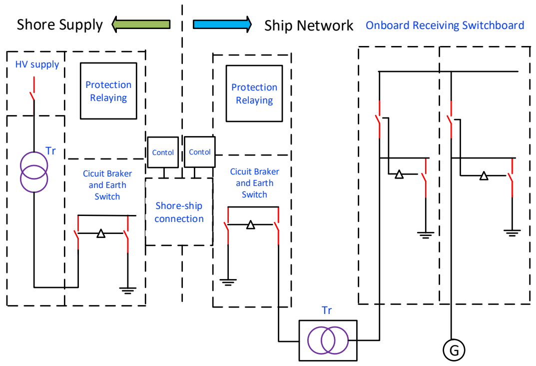

Fig. 1. Standard Shore to Ship Supply

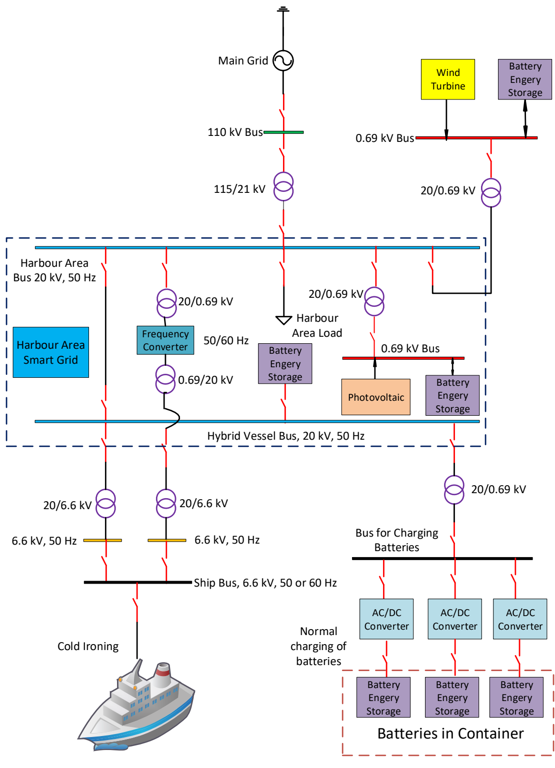

Fig. 2. Single Line diagram of Harbour Area Smart Grid

development of the hybrid vessels. Thus, it can change the current grid architecture, because the new grid design will require the charging stations at the harbour area. Therefore, the authors strongly recommend the development of new standards or the amendments in the current HVSC standard for providing the facilities of integrating DGs and charging stations with shore connection. The overall proposed concept of the HASG can be technically a key step in designing an innovative, pollution free and cost effective solution for the terminal operator, port administrator, and ship owner.

IV. Simulation results

The designed concept of the HASG is implemented using PSCAD/EMTDC simulation software. For validating the performance of the designed HASG, it is important to observe the response of the HASG under steady state and transient state of operations.

A. Steady state analysis

The data required for steady state simulation is given in Table I. The Table II shows that the voltage levels and frequency levels are maintained at all buses within the limits. Especially the voltage at the ship busses are within 3.5% voltage drop of the nominal voltage at the point of shore connection during cold ironing according to the HVSC standard requirement. The active and reactive power flows for the power supplying elements such as: main grid, WT, PV, BESs are taken with negative sign values whereas for power consuming elements such as load at harbour area, load for charging the batteries, shipload-1 for 50 Hz and shipload-2 for 60 Hz ship are taken with positive sign values. The difference of active and reactive power between the active and passive elements is the total power losses in the network (0.152 MW+j0.291 MVAr). Thus, the steady state results from the simulation model validate the designed concept of the HASG.

B. Transient state analysis

In the transient analysis, further, two case studies are considered, one of them from the perspective of disturbance from the grid side and another one from the viewpoint of the load side of the ship. The fault case study has been simulated in order to evaluate the performance of the HASG while considering the disturbance from the grid side. Whereas, the other case study has been taken from load side by considering a dynamically varying load of the ship during cold ironing.

1) Fault case study: The 3-phase-ground fault can cause a most severe disturbance when it is applied on any bus or transmission line of the HASG. The Fig. 3 shows the dynamic behaviour of the voltages at the busbars of the harbour area and hybrid vessel. At the time, t=5 sec, the 3-phase-ground fault has been applied for 0.2 sec on the bus where the WT is connected. Due to the applied fault, the voltage at the harbour area bus and hybrid vessel bus drop for the duration of the applied fault, but the voltage drop is within 10% of the rated voltage. Furthermore, the control action from the WT is so fast that the post-fault voltages recover to the pre-fault voltage level immediately after the fault has been removed. It is obvious from the simulation results of the fault case study that the designed model performs well under the transient state.

Table I. Data required for steady state simulation model

Components	Data
Main grid bus	110 kV, 50 Hz
Main transformer	115/21 kV, 20MVA, 50Hz
Harbour area bus	20 kV, 50 Hz
Hybrid vessel bus-1	20 kV, 50 Hz
Shore side transformer-1	20 kV/6.6 kV, 3 MVA, 50 Hz
Ship bus-1	6.6 kV at 50 Hz
Shore side transformer-2	20 kV/6.6 kV, 3 MVA, 60 Hz
Ship bus-2	6.6 kV at 60 Hz
Wind Turbine	3 MVA, 0.69 kV
Photovoltaic	1 MVA, 0.69 kV
Battery Energy Storage	2 MVA, 0.69 kV
Frequency converter	20 kV, 50/60 Hz
Load on Harbour Area Bus	(1.5+j0.3) MVA, 20 kV, 50 Hz
Load for Charging batteries	(1.8+j0.36) MVA, 20 kV, 50Hz
Ship Load-1	(2.4+j0.45) MVA, 6.6 kV, 50 Hz
Ship Load-2	2 MW, 6.6 kV, 60 Hz

Table II. Steady state simulation results of power flow

System Components	Voltage (kV)	Frequency (Hz)	Net P (MW)	Net Q (MVAr)
Main grid bus	110	50	-2.301	-0.1598
Wind Turbine	0.736	50	-2.734	-1.003
Photovoltaic	0.71	50	-0.943	-0.2618
Battery Energy Storage	0.707	50	-1.974	0
Load for harbour area	20.3919	50	1.559	0.3164
Load for charging batteries	20.2647	50	1.848	0.3699
Ship Load-1	6.58177	50	2.386	0.4469
Ship Load-2	6.61565	60.0035	2.007	0

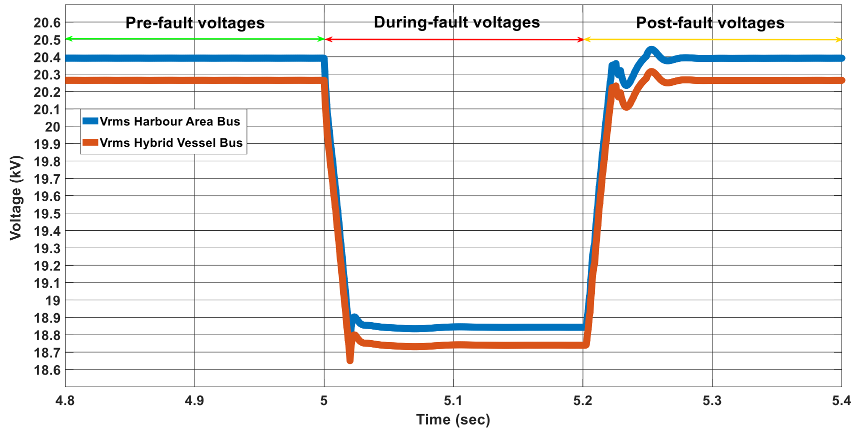

Fig.3. Simulation results of voltages at harbor area and hybrid buses during 3-phase fault applied on WT

2) *Dynamic load case study:* As the shipload during the cold ironing may not be the constant but varying with varying demands of an auxiliary load of the ship and some other loads like; crane load for loading and unloading. Thus, it is a realistic to simulate the load varying from no load to the dynamically varying load conditions, while considering the minimum and maximum load demand. The Fig. 4 shows the characteristics of dynamically varying load from no load to the nominal load of (1 MW+j0.15 MVAr) at t=2 s. The nominal load is taken as a reference load and varied to half of its rating at the time, t=5 s, again to the twice of its rating at t=10 s and at t=18 s the load is disconnected. The simulation results show that dynamic power demand of varying load is achieved smoothly and the Fig. 5 illustrates that the dynamic load voltage is also maintained according to the HVSC standard requirement within 15% of under transient voltage conditions of a step change in load.

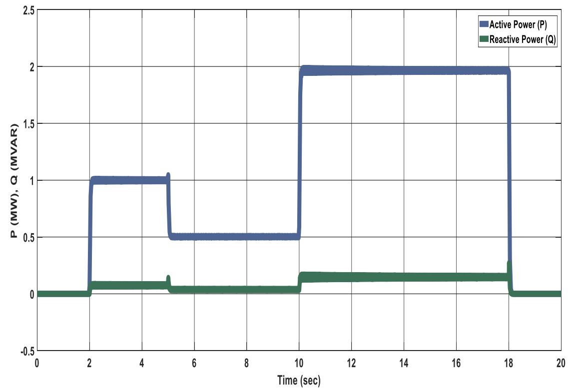

Fig.4. Simulation results of dynamic load power

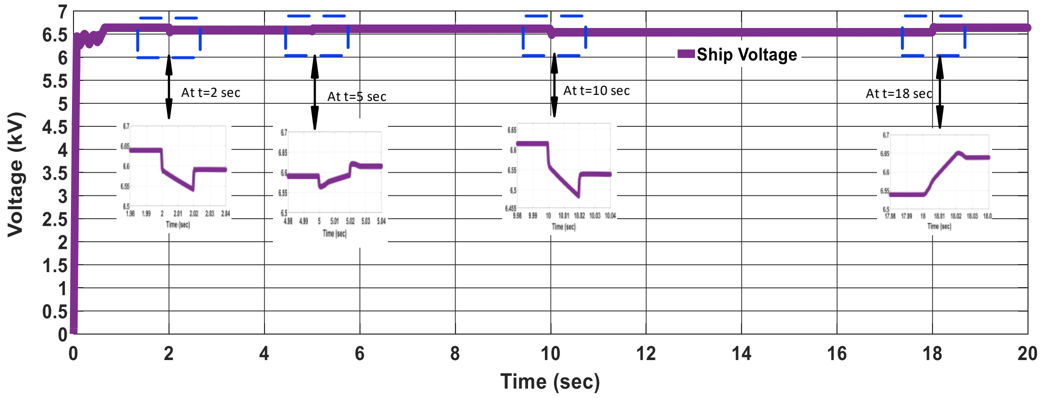

Fig.5. Simulation results of dynamic load voltages

V. CONCLUSION

The concept of local generation by DG operating in a new system concept of the HASG will not only provide a pollution free environment at the harbour area but also bring many benefits to the owners of hybrid vessels and seaports. The reliability and efficiency of the power supply will also be increased for harbour area consumers, terminal operators, port administration, and power utilities by employing power generation by the DGs at the harbour area. Here, along with highlighting the key issues of the harbour area, an innovative way of designing and modelling the harbour area smart grid are presented. The results from the simulation validate the performance of the designed HASG. Thus the proposed HASG, in addition to supplying the power to the vessels during cold ironing, can support the hybrid vessels by charging batteries at the harbour area. The charging of the batteries at the harbour area is a challenging task and in this regard, the authors strongly recommend the development of new standards or the amendments in the current HVSC standard. In future work, the authors are interested in islanded mode of operation of the harbour area smart grid while controlling the power generation and energy storages, cost/benefit for the proposed grid architecture and designing the optimal HASG to obtain standard size and dimensions of the equipment to be used as a module based HASG system.

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Review

Technical design aspects of harbour area grid for shore to ship power: State of the art and future solutions

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ABSTRACT

The cheap quality fuel used by diesel engines in marine vessels during a stay at berth is an environmental threat, and its widespread gaseous emissions are harmful to human health. Shore to ship power technology has been an essential requirement for reducing the emissions of maritime transport at harbour areas. Although this technology has already been implemented at certain seaports in several countries like the USA, Canada, Germany, Sweden, Finland, Norway, Netherlands, and Belgium, it is facing some technical and regulation problems. Shore to ship supply can be emission-free, economical and sustainable solution while utilising the renewable energy sources such as photovoltaic and wind energies along with battery energy storages. This paper aims to provide a comprehensive review of technical aspects, practices, existing standards and the key challenges in designing and modelling of a harbour grid for shore to ship power supply. This paper presents state-of-the-art and future marine solutions, discusses shore to ship power technology while considering voltage, frequency, power and other technical requirements of vessels at onboard and onshore. Moreover, this paper contributes in designing suitable models for the harbour area smart grids that can facilitate both onshore power supply as well as charging of batteries for the future hybrid and electric vessels.

1. Introduction

More than 90% of global trade is by seaborne vessels [1,2], and maritime transport plays a crucial role in the development of the world economy because it will be tripled in 2025 compared with 2008 [3,4]. However, it faces key challenges like dependency on fossil fuel, continuous increase in greenhouse gas (GHG) emissions, and some technical issues [1,5–7]. The current IMO report [1] predicted that increase in maritime CO_2 emissions by the end of 2050 would be 50–250% with respect to 2012 if some necessary actions for mitigating emissions and increasing energy efficiency would not be taken. One billion tons of carbon dioxide (CO_2) is from shipping, and the major sources of emissions to air from ships are main engines, auxiliary engines, and boilers [6]. There are various other types of emissions from the international shipping such as, carbon monoxide (CO), nitrogen oxides (NO_x), sulphur oxide (SO_x), volatile organic compound (VOC), ozone (O_3), and particulate matter (PM) [1,3,8–11], causing air pollution in harbour areas. Air pollution causes some dangerous health diseases including asthma, lung cancer, heart attack, chest infections and some other serious respiratory diseases [3,12–15]. These diseases are further responsible for about 60,000 deaths per annum along European, East Asian, and South Asian coastal areas [14]. Therefore, it is necessary to take the measures to avoid air pollution and preserve a healthy environment for the people, particularly in harbours. The concept of the green ship [2], green port [15,16], and zero emission port [17] will be the enabler for getting rid of emissions by employing renewable, sustainable and energy-efficient solutions at onboard as well as onshore.

In this regard, the IMO (International Maritime Organization) takes the actions for safe, secure and efficient international shipping by its regulatory framework and keeps an eye on shipping emissions, design, construction equipment, and operation. The IMO has set the international convention for the prevention of pollution from ships (MARPOL). It limits sulphur contents from ships in an Emission Control Areas (ECA) to 0.5% with effect from January 2015, and outside the ECA with effect from January 2020 or January 2025 depending on the outcome to be concluded by 2018. Currently, outside the ECA, the sulphur content limit is 3.5% by the MARPOL with effect from January 2012 [18]. European Commission is also striving to limit the emissions from maritime industry, set the rules, and implement the decisions in order to achieve the remarkable goals. The EU Directive 2005/33/EC [19], has recommended that the member states should use marine fuels with a sulphur content not more than 0.1% from January 2010 for the inland waterway vessels and the ships at berth in public ports. The EU Commission [5] has strongly recommended for cutting an overall EU

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transport emissions by 60% including 40–50% from shipping by the end of 2050 compared with 2005. In order to comply with the IMO, EU Directives, and EU Commission, ships have to switch the marine fuel from the traditional sulphur-rich Heavy Fuel Oil (HFO) to low-sulphur Light Fuel Oil (LFO) such as: Liquefied Natural Gas (LNG) [20–28], Marine Gas Oil [26,28], distillates (diesel) [24,28], biofuels [23,25,29], and the mix of biodiesel with conventional marine fuels (blends) [29]. The other alternative ways to significantly reduce sulphur content from the HFO is to employ scrubber technology [22–26,28] onboard and it will be an attractive option especially for large vessels [24]. Moreover, the LNG prices are expected to lower in the next few years, and EU Commission [21], also supports the growth of LNG as an alternative fuel for replacing conventional polluting fuels. Besides this, onshore power generation by LNG can also reduce sulphur and particulate emissions on ports [30].

There are several environmental indices for measuring the ship emissions, but some ports use an Environmental Ship Index (ESI) practically and offer the incentives voluntary to the ships provided that the ESI is within a certain limit [31] for promoting the clean ships to reach sustainability goals. The ESI is developed by the World Port Climate Initiative (WPCI) and used by the ports as a tool to measure NO_x, SO_x, PM, and CO_2 emitted by the ships [32]. The California Air Resources Board is taking the measures for controlling toxic gases and emissions to air from auxiliary diesel engine operated by sea-going vessels, and it has set the regulations known as At-Berth Regulation. This regulation has directed to reduce and replace the onboard generation at berth by 80% from January 2020, either by shore-side electricity or with any other option of an equivalent emission reduction [33]. The EU 2006/339EC [34] demonstrates the shore-side electricity as a tool for improving air quality and human health nearby ports by reducing air pollutant emissions.

The ocean-going ships are considered as floating power plants because onboard power generation is high and it varies from few kilowatts to tens of megawatts [30] depending upon different types of the vessels. Conventionally, main diesel engines generate electric power for propulsion of vessels for manoeuvring and auxiliary diesel engines for ships services and their stay at the berth [4,6,35,36]. When vessels are at berth, typically they are using electricity for different purposes: lighting, ventilation, cooling, heating, communication, hoteling, loading and unloading [4,6]. The process of switching off all the diesel engines of the vessels while at berth and supplying the power to the vessels by shore-side electricity is usually termed as cold ironing. The term cold ironing is also well known in the literature by different names such as Shore-to-Ship Power, Shore-to-Ship Electrification, Shore-to-Ship Connection, Ship-to-Shore Connection, Shore Side Electricity (SSE), Shore-Side Power Supply, Shore Connection, Onshore Power Supply (OPS), Alternative Maritime Power (AMP), Alternative Marine Power System, and more recently High Voltage Shore Connection (HVSC) [2,4,6,8,12,18,37–40]. Initially, the U.S Navy used the term cold ironing when all ships had coal-fired ironclad steam engines. It was necessary to cool down these engines during a stay at ports, and ultimately these engines became completely cold [39]. Before the HVSC standard, many ship designers, ship owners, and port authorities were endeavouring to have a compatible system for the cold ironing in the world [41,42]. Currently, the HVSC standard [37] is a harmonized international standard set unanimously by the world leading organisations: IEC, ISO and IEEE for solving the technical issues of shore-side electricity.

The design of a harbour grid is a challenging task while taking into consideration environmental issues, technical issues including safety and protection issues, standard regulations, and continuous development in the field of marine technology. Harbour grids should be designed in such a way that it can solve multiple problems: reduction in emissions, dependency on fossil fuel, compliant with the power requirement of cold ironing and facilitating charging of batteries for future hybrid and electric vessels [41]. Renewable Energy Sources (RESs) at harbour area can reduce an overall carbon mass per kWh of electricity generated to a minimum value as compared to the mass of carbon exhausted by auxiliary engines at berth, i.e., 690–722 grams per kWh of electricity generated [9]. The objective of this comprehensive research work is to focus on state-of-the-art technology development in shipping and shore-ship power supply. This paper explains the existing practice, standards, barriers and technical challenges in implementing shore-ship power supply and future marine solutions. Moreover, this paper contributes to designing and analysis of the key features of some suitable models for the Harbour Area Smart Grid (HASG) that can supply power for ship's services during a stay at ports as well as charge batteries for future hybrid and electric vessels. The rest of the paper is organised as follows. Section 2 describes how cold ironing can be an emission-free and sustainable supply for the vessels berthed at the seaports in the harbour area. It highlights on adopted voltage levels and frequencies of the power supply of the ships at onboard and their associated voltage, power and cable requirements at onshore. The barriers and technical challenges in implementing onshore power supply for vessels are also discussed in this Section. In Section 3, present and future marine solutions for onboard and onshore are outlined. Section 4 focuses on designing the HASG and presents some modified models of the HASG, which are suitable for shore to ship power supply. The conclusion is presented in Section 5.

2. Onshore power supply: state of the art

This section addresses the fundamental questions: why an onshore power supply is necessary, how the onshore supply can be clean and sustainable, and why the onshore supply is necessary even if national grid electricity is more expensive and pollutant compared with electricity generated from auxiliary ship diesel generator. The several voltage levels and frequencies adopted by the vessels at onboard, standard onshore voltage and power requirements, cables and their connection requirements for shore to ship power supply for various types of the ships are also mentioned in this section. Since the voltage and power requirements of different kinds of the vessels are different, this section may help to familiarise with these requirements before designing a shipboard and onshore power system. Moreover, this section also outlines the main business barriers, key technical issues, and challenges of designing a harbour grid for shore to ship power supply.

2.1. Onshore power supply as an emission-free and sustainable supply

Onshore power supply is a suitable solution to make ports and harbours free from greenhouse gas (GHG) emissions, air pollutants (NOx, Sox, PM), vibrations, and noise pollution [6,8,11,18,34,37,38,40,42]. It has also been evaluated by the operational profile of a real case of RoRo vessel sailing between France and Spain that by applying the onshore power supply along with onboard Battery Energy Storage System (BESS) can significantly save fuel and emissions emitted by the ships [43]. Even with the onshore generation by the LNG can reduce CO_2 emissions by up to 40% [30]. Moreover, an application of the shore-side electricity can be emission-free, self-sustainable, reliable and efficient while utilising a maximum mix of RES into national grid supply [2,9,41,44]. Therefore, electric power generation from renewable sources by Distributed Generation (DG) such as solar, Wind Turbine (WT), geothermal, tidal, and wave energy resources at harbour area nearby the seaports [8,17,39,45,46] will be a suitable option to have an economic as well as a clean energy because they produce relatively low greenhouse gas [47]. The higher penetration of RES in the HASG can protect harbour area from the environmental pollution and bring many benefits to the terminal operator regarding saving the cost due to heavy demand charges billed by the utilities [45] and improving reliability and efficiency of power supply [47–49]. In future, a large energy storage [50,51], and plug-in hybrid power systems [52] might be a preferred option for ship services during a stay at onshore for zero-emission operation.

It has been observed that emissions from electricity generation into national grids depend on mix of renewable-based power sources [53]. The emissions per kWh of electricity generation from auxiliary diesel engine berthed at ports may vary worldwide depending on the quality of fuel used and can be compared with the emissions per kWh of power generation from the national grid of any maritime country. The onshore power supply is the most appropriate option in the maritime countries such as; the United States, United Kingdom, Germany, Japan, Norway, Italy, France. In these countries, emissions per/kWh from the ship's auxiliary diesel generator are more than that of the national grid. However, there are some countries like China, Russia, and United Arab Emirates, where the shore power supply leads to a substantial increase in overall emissions [9]. From an economic viewpoint, shore-side electricity can be cost-effective in those maritime countries where electricity prices are lower than 0.19 USD/kWh but may not be economical for the countries such as Singapore and Brazil where the national electricity prices are higher than 0.19 USD/kWh [54]. However, it does not mean that the onshore power supply should not be implemented in those countries where emissions from national electricity grid are more than that of the auxiliary diesel engine power generation of the ships, and electricity prices are higher than 0.19 USD/kWh. Onshore supply has an additional advantage that it moves the pollutants from populated areas such as harbours to remote locations where the power plants are located, thus providing the localized emission-free solution at the ports [6,30].

Sweden was the first country who installed the commercial onshore power supply in 2000 at the port of Gothenburg [55]. Table 1 shows the implemented ports in the world with high voltage shore-side electricity along with their power capacity, available power supply frequencies and the types of the ships facilitated by the onshore supply. Apart from this list, some other countries, for instance, France, Italy, Spain, Latvia, Estonia, Japan, and China are also planning to implement the same technology in their ports [2,4,20,42,56].

2.2. Vessels with their electrical characteristics at onboard and onshore

There are several types of ships depending upon the functionalities such as cruise ships, LNG carrier ships, container ships, and Ro/Ro ships. These ships can further be classified based on power requirements at the onboard and onshore side during a stay at ports. Currently, most of the vessels operate on low-voltage (380–460 V), except few vessels [4]. At present, 75% of the vessels have 60 Hz, and the remaining 25% of the vessels have 50 Hz power supply frequency at onboard globally [57]. Fig. 1 shows that most of the large cruise ships and very few large container vessels operate on high voltage, and the rest of all the vessels operate on low onboard voltage.

Table 2 depicts the voltage level and power requirement for the various vessels on shore side according to the HVSC standard requirement along with the information of cable interface and a minimum number of the cables required to cope with the power requirement of the specific vessel.

2.3. Barriers and technical issues for shore to ship power supply

The different power capacities and size of onshore power installations will have different impacts on local power grids as well as on business cases. The shore to ship power supply is the today's technology for a rapid growth of maritime transport but still not well-established, young technology and having some barriers in implementing practically. The barriers may be from the perspective of stringent policy actions and legislation [2], business case, technical viewpoint, and lack of interest from the local or regional governments and worldwide. The barriers from the business case perspective of onshore power supply are the following [20]:

1. Who should invest on shore to ship power infrastructure? There can be several options such as utilities of power supplies, port owners, ship owners, local governments or partial involvement of port owners and ship owners.
2. There is a high initial retrofit cost on individual vessels for complying with the IMO requirements and shore connection capabilities.
3. There are taxes on using electricity by the onshore power supply at some regions whereas there is no tax on electricity generated by vessels using fossil-fuel based auxiliary diesel generators while staying at harbours.
4. There can be limited or unused onshore power supply infrastructure at some ports, which may not be suitable for a business model.

Besides business barriers, designing harbour grids needs careful attention to meet technical requirements, especially the power requirements of the harbour area load, cold ironing load in addition to battery charging load of the modern hybrid and electric vessels. The existing cold ironing power requirements can be categorised into small

Table 1
World ports with shore power supply [20,56].

Year	Port Name	Country	Capacity (MW)	Voltage (kV)	Frequency (Hz)	Ship types
2000–2010	Gothenburg	Sweden	1.25–2.5	6.6 & 11	50 & 60	RoRo, ROPAX
2000	Zeebrugge	Belgium	1.25	6.6	50	RoRo
2001	Juneau	U.S.A	7–9	6.6 & 11	60	Cruise
2004	Los Angels	U.S.A	7.5–60	6.6	60	Container, Cruise
2004	Piteå	Sweden	1.0	6	50	RoRo
2005–2006	Seattle	U.S.A	12.8	6.6 & 11	60	Cruise
2006	Kemi	Finland		6.6	50	ROPAX
2006	Kotka	Finland		6.6	50	ROPAX
2006	Oulu	Finland	1	6.6	50	ROPAX
2008	Antwerp	Belgium	0.8	6.6	50 & 60	Container
2008	Lübeck	Germany	2.2	6	50	ROPAX
2009	Vancouver	Canada	16	6.6 & 11	60	Cruise
2010	San Diego	U.S.A	16	6.6 & 11	60	Cruise
2010	San Francisco	U.S.A	16	6.6 & 11	60	Cruise
2010	Karlskrona	Sweden	2.5	11	50	ROPAX
2011	Long Beach	U.S.A	16	6.6 & 11	60	Cruise
2011	Oslo	Norway	4.5	11	50	Cruise
2011	Prince Rupert	Canada	7.5	6.6	60	
2012	Rotterdam	Netherlands	2.8	11	60	ROPAX
2012	Ystad	Sweden	6.25–10	11	50 & 60	Cruise
2013	Trelleborg	Sweden	3.5–4.6	11	50	ROPAX
2015	Hamburg	Germany	12	6.6 & 11	50 & 60	cruise

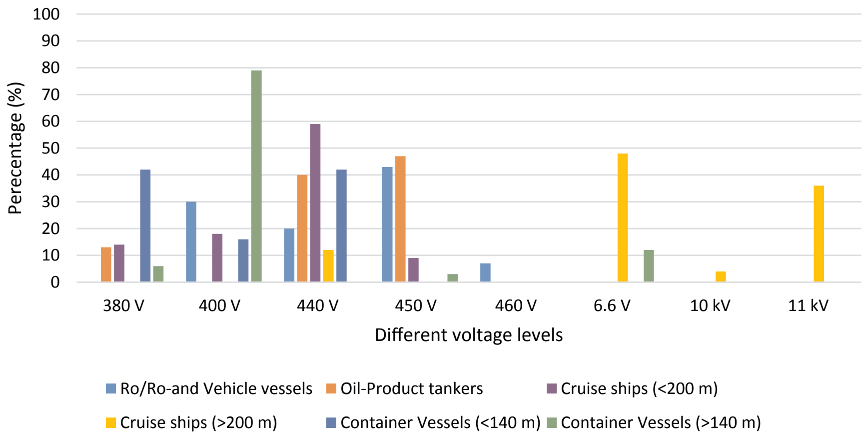

Fig. 1. Onboard voltage levels of the vessels [4].

Table 2
Vessels with onshore voltage and power requirements [37,58].

Ship type	Voltage (kV)	Power (MVA)	No. of cables	Cable interface
Cruise ships	6.6 or 11	16–20	4	Shore Side
LNG carrier	6.6	10.7	3	Shore Side
Container ships	6.6	7.5	2	Ship Side
Tankers	6.6	7.2	2	Shore Side
Ro/Ro ships	6.6 or 11	6.5	1	Shore Side

ship power requirement (less than 1 MW), large cruise power requirement (less than 12 MW), and container vessel power requirement (2 to 12 MW) [39]. The ports like Eastern EU ports have a limited capacity to cope with maximum power demands of the visiting vessels [20], this can cause grid stability problems. Besides power demand, some unique power system components for the switching, cable management, plugs, and receptacles are needed [59]. The design of over-current protection is also a very complex due to the particular behaviour of the frequency converter in the harbour grid [40], and more protection and safety is required also due to frequent switching operation of breakers [59]. Therefore, harbour grids must comply with the electrical characteristics, power protection, and safety issues as described by the HVSC standard.

Shore to ship power is supplied to the vessels by some special flexible power cables either at onshore or ships, depending on suitability and available infrastructure on ships and shore [37,44]. There are several possibilities for handling cable connection of shore to ship supply, such as manual, or with a crane and electric drum. In the past, cable connections were made entirely manually because of small power requirements, and size of the cables did not exceed 35 mm in diameter. But currently due to higher power demand, the cable connection with cranes is an easy solution, and it also reduces personal aboard [2]. As technology advances, in future, the cable connection of shore to ship power might be with the industrial robots as the first automated connection of shoreside charging station by using the robot is in progress [60]. The voltage drop for shore power supply may cause several problems. Therefore, the analysis of voltage drop is an essential and can provide a basis for one-time-establishment cost at the beginning of construction of a wharf [58]. After connecting shore to ship cable, the synchronization of shore power supply with shipboard power system should be smooth and uninterrupted [30]. Two synchronization operations are required, one for transferring the auxiliary load of a ship to shore and another for transferring the load back from shore to ship's auxiliary generator [59].

The key challenges in designing harbour grids are to match the voltage and frequency of shore power with the ship power. A shoreside power transformer complying with the HVSC standard voltage is required, but this transformer should be with low no-load losses because it is energized even when a ship is not connected to shore power supply [59]. For matching the frequencies of the onshore and onboard power system, a frequency converter is required to provide power to the vessels operating on 60 Hz onboard at the harbours which have 50 Hz power supply and the vice versa. A frequency converter must be designed on a modular basis to fulfil the various power requirements but not necessarily by standard size, because it is one of the most expensive equipment of a harbour grid [4]. There are mainly two types of frequency converters: static, and rotary frequency converter [2,55], but each type has its advantages and disadvantages. The static converter utilising the modern technology of power electronics is preferred over the rotary frequency converter due to small size, high reliability, low losses, and low civil work required for installation [55]. However, the frequency converter should also comply with the HVSC standard requirements [37]. There might be several configurations or topologies of frequency converter [4,30,39] for shore to ship supply but two configurations are mature namely centralised and decentralised [55]. The centralized frequency converter configuration being cheap and less space occupying solution at harbours is preferred, but it may face the problem of reliability because if a fault occurs on the central frequency converter will affect all the vessels. The decentralised frequency converter is more reliable because every ship is supplied with its frequency converter on the berth, but it is expensive and requires more space in harbours.

3. Present and future marine solutions

This section provides the current development of shipping industry and future marine solutions for onboard as well as for onshore power supply. The development in shipboard power systems decide new research directions and development in designing a harbour grid. How the current paradigm is about to change with future hybrid and all electric vessels is also explained in detail in this section.

Shipping technology is developing continuously and rapidly mainly in the directions of both propulsion topology and power supply topology [61]. Ship propulsion system has evolved from mechanical to electrical and currently towards the hybrid system, whereas shipboard power system has recently developed from combustion to electrochemical, stored and integrated power systems [62]. The modern all electric ship (AES) has an integrated power system, consisting of several generators including renewable sources and energy storages and behave like an islanded microgrid with a power capacity of up to 100 MW [63–66]. The AES is supposed to be the most efficient ship replacing the conventional mechanical system with electric propulsion. The concept of AES has become a standard for large cruise ships adopted by major shipyards in the world [64] and also applied on the shuttle tankers, ferries and some particular types of vessels [65]. The breakthrough of this era came in 2015 when the world's first battery-operated ferry (Ampere) was launched in Norway [67]. The rapid development of research and technology in battery storage, power electronics, and information technology can open a modern era for the vessels by applying wireless charging of batteries [68], real-time measurement, and monitoring of the fundamental parameters of the ships [69].The example of the boat-sail boat [70], and the hybrid green ship (PV/diesel) [35] in the island of Geoje, South Korea describe the possibility of retrofitting the photovoltaic generation and the BESS with a diesel engine. Commercially, several ships have been retrofitted with large BESS including the first installation of 2.7 MWh battery in a hybrid configuration of the Scandlines' Prinsesse Benedicte, operating between Denmark and Germany [52]. Norway introduced the world's first electric-powered ferry named Ampere (ZeroCat) in 2015, launched by a collaboration of Fjellstrand, Siemens, and Norled [67]. Finland is for the first time presenting hybrid ferry named FinFerries Elektra designed by CRIST and SIEMENS [71].

In future, the conventional ship power system using fossil oil will shift towards integrated power system, consisting of renewable fuels [7], sustainable and energy storage solutions for decreasing use of fossil fuel, increasing energy efficiency and reducing GHG emissions [50]. Biofuels as a sustainable fuel can replace the fossil fuel in future and can be suitable for 100% renewable energy system for transport [52,72,73] particularly for the large ships with high power requirements. Currently in addition to fuel, the primary energy storages are used on ships such as capacitors, flywheels, and battery storages. These energy storages are suitable for spinning reserve, faster response to a dynamically varying load, delivering a pulsed load power, strategic loading, improving operational efficiency and optimising fuel consumption [50]. Since each energy storage has its characteristics, specifically energy density and power density, their application is subjected to the requirements of the vessels [51]. The appropriate selection of energy storage technology may also be used to mitigate power quality issues of a ship's microgrid [74]. The BESS with some control action can also be suitable for smoothing power fluctuations in a weak grid of a ship [75] will be suitable for future high power applications [76]. The Li-Ion (Lithium-Ion) family derivatives batteries having high energy density and power density are useful for shipboard applications [52], and the marine certified packages are also available commercially in the standardised 20-foot containers with capacity up to 1 MWh [43]. Besides this, Li-Ion batteries are developing fast with decreasing cost, maintenance-free and have a long life with more than 1000 cycles at 80% depth-of-discharge [77]. Conclusively, keeping in view the past five years track record, the battery-powered vessels are developing fast [52], and energy management of the modern shipboard power system is a challenging task due to multidisciplinary and interdisciplinary involvement of the fields of internal combustion engines, electric power generation from various sources, battery technology, and control engineering [51].

Fig. 2 illustrates how the current state-of-art of ship power system will shift from non-renewable to the renewable sources of energy in future. Currently, ships are gradually moving towards the LNG particularly due to stricter rules from the IMO and the EU-Directives. The LNG produces fewer emissions compared with the diesel or other fossil fuel [30] and is being employed as the marine fuel for several ferries in Norway [78]. The technical advantage of using LNG fuel is achieved by adopting dual engines that can run on either LNG or fossil oil, with a use of a minor amount of fossil oil for ignition [7]. In future, large ships will have a hybrid power system at onboard consisting of fossil fuel or biofuels [79] as a primary source along with the RES and BESS. Fuel cells can also be a primary source of power supply in the microgrids of the ships [74]. In this regard, the feasibility of integrating solid oxide fuel cell with gas turbine along with absorption heat pump in a tri-generation system for marine application has been investigated and found useful for improving the overall efficiency and reducing the emissions. Although hydrogen fuel is compatible with the majority of fuel cell systems, it has the major drawback that it has relatively lower power density and consequently large volume required for the storage. Therefore, hydrogen fuel cannot be used for the large ships as a primary source of fuel. However, it can be best suited for the ships requiring low power and have the facility of regular refuelling [78]. The current and future inclination for the ships with short-distance route and small power requirement is towards emission-free solution by employing the BESS as the main source of power supply. Moreover, due to the rapid development of battery technology and reduction in battery prices, it is claimed that the BESS, especially Li-Ion, will eventually be an important part of the shipboard power system of modern hybrid and all-electric ships [50,52,63,68,69]. Therefore, following the development of shipping technology, future harbour grids have to be carefully designed to cope with the need of modern vessels.

The current paradigm of ships and harbour grids is about to change with a particular focus on the application of cold ironing and facilitating the charging stations for the batteries of future hybrid and electric vessels [41]. Recently, wireless-high-power charging of ship batteries has also been developed, tested and demonstrated by Norwegian marine industry in the laboratory environments for power levels exceeding 1 MW and the first pilot installation is expected for regular operation during 2017 [68].

4. Designing a harbour grid

This section explains that how a port can optimally balance power, gives a brief overview of the current HVSC standard, and presents some suitable solutions for harbour grids along with technical analysis.

Port power system has to optimise energy consumption by employing the advanced and innovative solutions such as local energy generation, energy storage, automated cranes, automated guided vehicles and advanced reefers [80]. The concept of smart grid for ports can be a viable option while considering a great potential for local energy generation by renewable energy resources [17,81], and flexible loads like refrigerated containers, electric vehicles [46,81], and charging of batteries [41]. Therefore, the above flexible loads can easily be controlled by shift in time [46], so that the goals of peak reduction and energy efficiency can be accomplished. Some intelligent techniques like pattern recognition [82], and multi-agent systems [81] can also be used for optimising the load demand and power management. Onshore power supply to ship can be turned into smart-load by applying energy storage interface which can be charged during low energy demand [83]. Moreover, onshore power supply to ship can also be turned into a flexible power producer while considering power generation from ship's auxiliary generators [81,84].

By using the concept of smart port [70] the electricity at the ports can be exchanged between hybrid or electric vessels and ports but needs the harbour infrastructure to sell this energy to the market. The idea of wise port [45] mentions the necessity of microgrid at the seaport and assumes the harbour area as a single territory that should focus on feasible and smart management of electricity from a business perspective. By using the wise port concept, the electricity at the port can be exchanged between the port and the national grid on an economic basis. The idea of combining smart grid with cold ironing concept, which can provide several advantages, has been proposed in [39,83]. The port is supposed to be a concentrated large load as compared with a conventional smart grid where small loads are geographically dispersed. The detailed analysis of future harbour grid is given by the HASG in [41] by introducing HASG, which can support not only the cold ironing load but also a load of charging the batteries for hybrid and electric vessels.

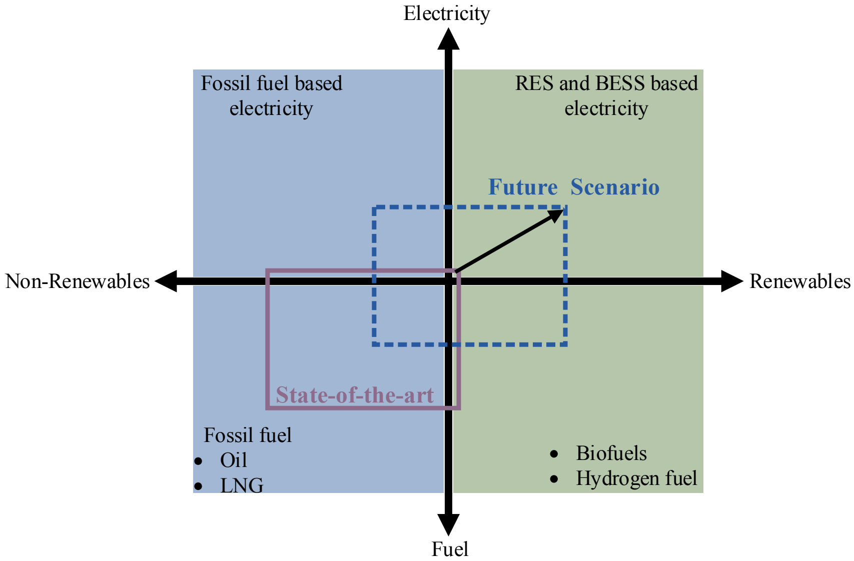

Fig. 2. Present and Future Onboard Power System of Ships.

4.1. Standard high voltage shore connection

The current HVSC standard [37] has solved many technical issues regarding onshore power supply mainly fixing the high voltage for shore connection (6.6 kV or 11 kV). It sets the limits of voltage deviations during steady state and transients, highlights the possible power quality issues and the standard limits on total harmonic distortion level. Beyond this, the HVSC standard has explained the requirements of many other electrical characteristics, power protection, and personal safety issues in detail. This includes short-circuit current contribution level from shore and ship, establishment of equipotential bonding between ship's hull and shore earthing electrode along with self-monitoring device, the value of the neutral earthing resistor for the shoreside transformer, plugs, sockets, switchboards, maximum power capacity limits of each cable, and minimum power capacity for shoreside electricity attributed to each vessel. The HVSC standard also describes the compliance of rotary or static frequency converter requirement for the shore connection. In addition to the shore power standard requirements, the HVSC standard has also highlighted the ships' standard requirement for satisfying with power system protection, safety, monitoring and some general issues. Fig. 3 presents the HVSC schematic diagram, which consists of mainly onshore supply and ship's networks. The circuit breakers, protective relays, control and communication cables are in between these two networks for the interface between the onshore and onboard systems. Moreover, shoreside transformer in between onshore and onboard supply is used to transform high voltage power supply with the less number of cables compared with low voltage power supply for the same amount of power required at onboard for the vessels, and provide a galvanic isolation for the connected ship from another ship or consumer.

4.2. Harbour area smart grid

Recently the concept of the HASG is given in [41], as shown in Fig. 4, which is designed, modelled and validated in PSCAD/EMTDC software for supporting the harbour area load, cold ironing load and facilitating the hybrid and electric vessels for charging the batteries in the harbour area. In this design, the Harbour Area Bus of 20 kV is the bus for common coupling, which is supplied by the main grid, the HASG, and the WT near to the harbour area. The HASG consists of photovoltaic as a DG and the BESS at various locations for the sake of reliability and stability of the whole power system. The hybrid vessel bus and the frequency converter stations are located nearby the seaports in the harbour area. The frequency converter is used to convert 20 kV, 50 Hz to 20 kV, 60 Hz for supplying power to the vessels operating at 60 Hz during cold ironing. Two shoreside transformers are connected with hybrid bus and the frequency converter station to step down the voltage from 20 kV to 6.6 kV at 50 Hz and 60 Hz respectively. A shoreside transformer is required according to the HVSC standard to isolate galvanically one ship from another ship or consumer. However, this may not be mandatory in case if a dedicated HV shore supply transformer is available at onboard. Thus, two dedicated ship buses or double bus bar are required to provide power to the ships at 50 Hz and 60 Hz. The main objectives of the proposed single line diagram are supplying the power to the ships during cold ironing as well as charging the batteries in an onshore container for hybrid ships.

Li-Ion batteries having high energy and power density [85] as well flat discharge voltage characteristics during most of the time [86] are suitable choice for marine application [63]. They can be charged inside a movable container with 0.69 kV, which complies with the Low Voltage Shore Connection (LVSC) Systems [87]. Each battery inside a container is with 2 MWh capacity, charging rate of 0.1 C, and can be replaced with the discharged batteries of hybrid vessels during cold ironing time.

The main concept behind integrating WT and PV into harbour grid is to get renewable and sustainable energy for getting emission-free generation by employing them as a DG. The DG has a relatively low capital cost compared with central power plants and can reduce losses in the transmission system [49,88,89] of utility supply. The DG units should be located near the main load at harbour area to avoid the expansion of the existing network [41]. Often the output power of DG units is unpredictable because many RESs are intermittent in nature [90]. Consequently, the penetration of DG can raise the concern of unreliable and unsatisfactory operation [85] in the harbour grid. To get advantages from the DG, the integration of energy storages [90] is a feasible option to improve reliability and stability [85] of the HASG, especially in island mode. The battery technology as energy storage will play a significant role in the marine application due to decline in battery cost [70], progress in performance [63] and reliability [85].

In Fig. 4, the HASG consisting of the RES (PV) and the BESS inside

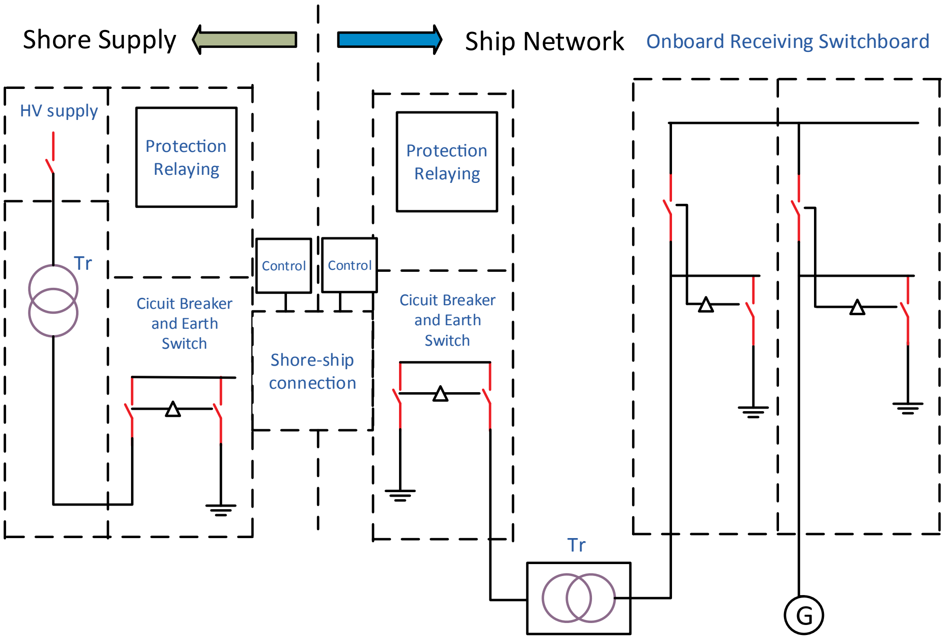

Fig. 3. Shore to ship supply [37,41].

port has a common coupling with the main grid power supply and RES (Wind Power) near to harbour area. In this configuration, the power exchange with the main grid is supposed to be controlled in co-ordination with all the power supplying sources including the BESS. From technical viewpoint, the BESS is suitable for the ancillary service applications such as voltage support, black start, and frequency regulation [91]. In the grid-connected mode, the application of BESS in the harbour area smart grid (HASG) can smoothen the power fluctuations of RES onshore in harbour areas and support the weak grid in case of power unbalance, power stability and power reliability issues. Whereas in the islanded mode of operation of the HASG, load shedding may not be a viable option due to the important schedule of the vessel's stay at a seaport, therefore, the BESS as a master unit can control the HASG power balance, so that uninterrupted power supply can be maintained. Besides this, a BESS facilitates for other applications such as energy arbitrage and peak shaving [90] in the HASG.

There can be several modifications in designing the HASG as compared to the designed model in [41], but this paper presents two modified versions which can be suitable from the technical and economical viewpoint. The explanation of these models, their key characteristics, and technical analysis on all harbour grid configurations are provided in the subsequent sections. This paper mainly focuses on alternative design configurations of the HASG and their feasibility, which depends on many factors including availability of infrastructure and space at a port, and the vessel's type and its staying time at a port, and power and energy demand of port. However, the comparison of these models in detail with some indices such as power losses, energy efficiency and costs is left for future research work.

4.2.1. Harbour area smart grid modified version-1

The modified version-1 of the HASG is shown in Fig. 5, which presents the following changes concerning the schematic diagram of Fig. 4. The main ideas here are to make the hybrid bus with 0.69 kV instead of 20 kV, and to use a single transformer instead of two for both 50 Hz and 60 Hz vessels. However, this single transformer must be designed for 50 Hz for supplying power to both 50 Hz vessels, and 60 Hz vessels, or in another case the inside windings of the transformer can be damaged, if it is designed for 60 Hz supply and operated on 50 Hz, due to a decrease in reactance and increase in current. The interlocking switch is placed for safety and protection so that either 50 Hz or 60 Hz vessel is energised at once. When compared to the HASG in Fig. 4 this configuration can save in total four transformers: one transformer which was required for charging the batteries, the other transformer which connected photovoltaic and BESS inside the HASG to Harbour Area Bus, 20 kV, and two more transformers which were placed to connect frequency converter between Harbour Area Bus, 20 kV and Hybrid Vessel Bus 0.69 kV. Thus, the modified HASG reduces half of the number of transformers and their associated protection equipment, consequently decreases the overall cost of the HASG as well as space on seaports compared with the design model in Fig. 5. In addition to these significant modifications, some minor changes have been done in the schematic diagram for more clarity. These changes are made by inserting AC/DC converters wherever necessary, renaming wind turbine with wind power, and battery energy storage with BESS.

4.2.2. Harbour area smart grid modified version-2

A further modification in the design model of the HASG concerning the schematic diagram of Fig. 5 is shown in Fig. 6. The main difference in the design model between the schematic diagrams in Figs. 5 and 6 is the replacement of the frequency converter with the battery inverter supply. As compared to Fig. 5, the location of the BESS has been changed and the BESS in this concept will provide the dedicated supply for the 60 Hz vessels, thus frequency converter will be no more required. The main idea behind the concept is to replace a capacitor inside the frequency converter by the BESS; which enables downscaling the power ratings and power supply for AC/DC converter to charge batteries, and lowers peak power ratings of the concerned grid components used to supply the converter. Ultimately, this configuration can reduce the overall cost on the whole system including the BESS and power supplying equipment from the grid. This configuration is especially suitable for the harbours having weak grid system, because it enables less power demand from grid by charging the BESS at the rate of 0.1 C, while the cold ironing load can be supplied from the BESS at the required power level. This configuration has also an additional

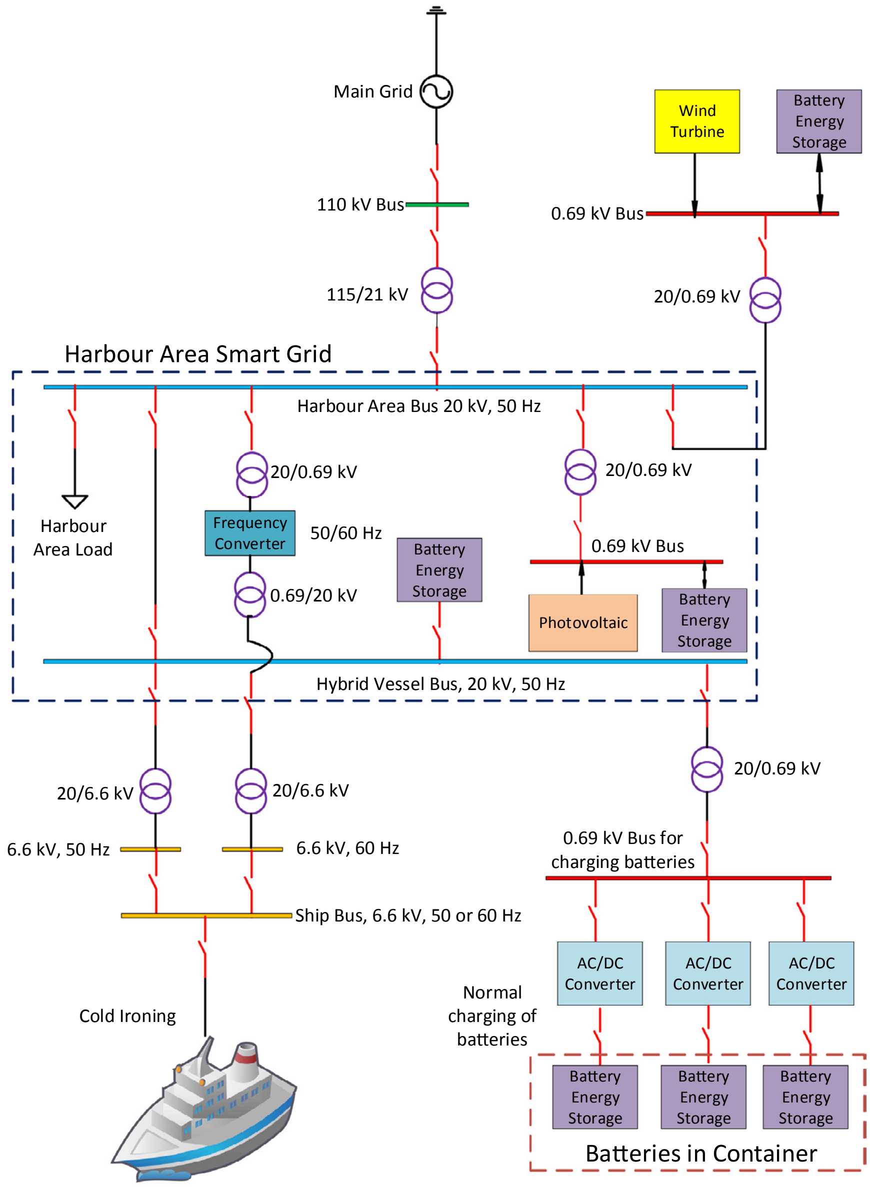

Fig. 4. Harbour Area Smart Grid [41].

characteristic of shifting energy demand by charging the BESS at off-peak time and supplying energy when demanded. As the research and development in the BESS progresses very rapidly and its prices drop drastically, the BESS can be technically a viable option while taking into account the possible integration of BESS on large scale with national and distribution networks. Moreover, this solution would be more suitable for those 60 Hz vessels, which do not require significant amount of the energy for cold ironing, and their stay at 50 Hz ports is for short time, and less frequent. This solution having less equipment compared to the other configurations will occupy less space at harbours in comparison with the previous two design models. This design concept primarily depends on battery storage system, therefore, the power capacity of battery storage must be higher than required for the cold ironing load of 60 Hz vessels specifically. Up to the best knowledge of the authors and literature surveyed so far, this solution is a novel technique and it can be useful in the field of shore to ship power supply.

4.2.3. *Technical analysis and validation of the proposed models*

The key aspect in designing the HASG is to comply with the technical requirements of the HVSC [37] and LVSC [87] standards. The main challenges in designing the HASG is to match the voltage and frequency of onshore power supply with ship power system. Besides this, the other key issues in designing and modelling of the HASG are case specific, depending on multiple factors: possibility of utility power supply, types of vessels commonly visiting the port and its energy and power demand during stay at the port, and possibility of local generation and energy storage at port.

The harbour area smart grid model presented in [41] has been validated by steady state and transient case studies. The voltage and frequency at different buses especially voltage on ship bus is

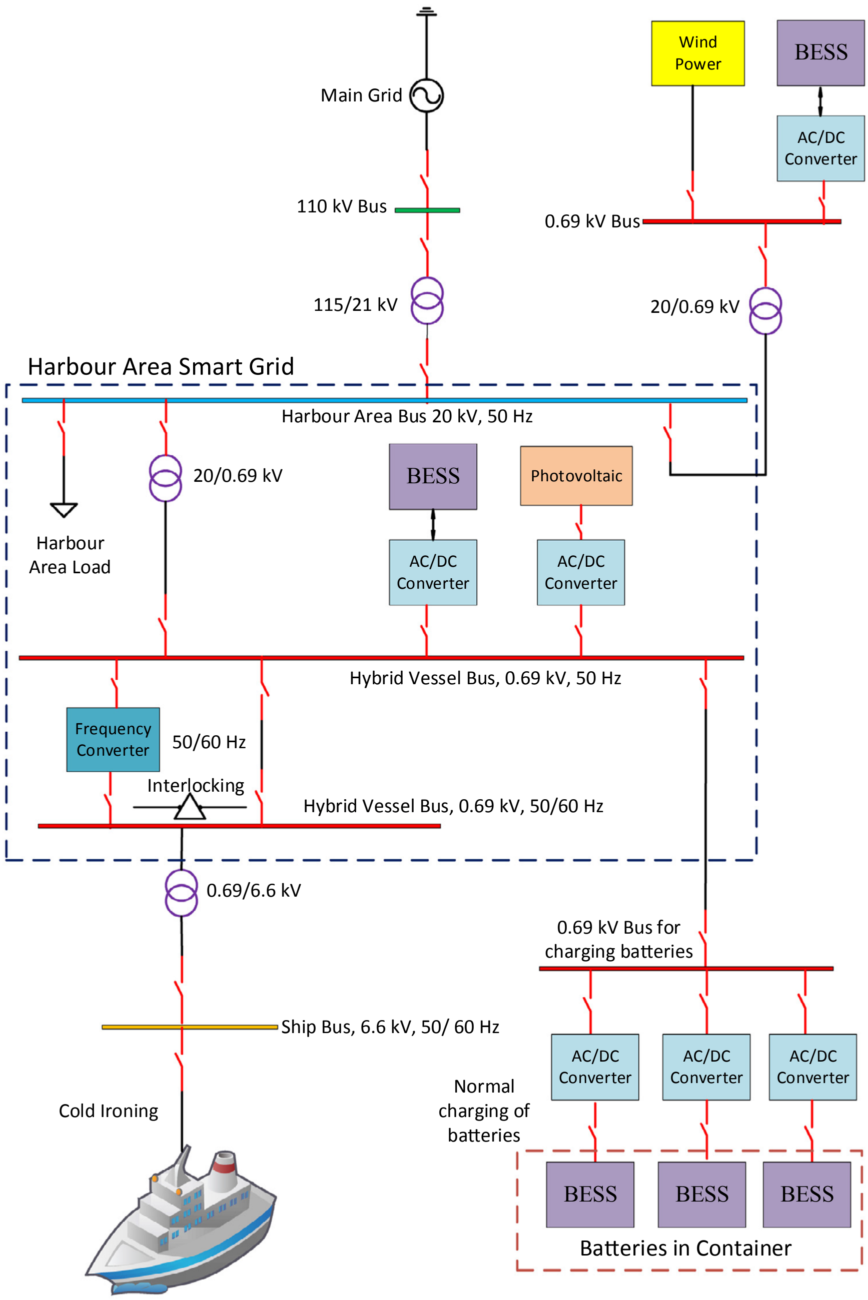

Fig. 5. Harbour Area Smart Grid modified version 1.

maintained within the specified limits of 3.5% of voltage drop according to the HVSC standards [37]. Both modified versions of the models introduced in this paper differ with the HASG model on component level; however, they provide the same functionalities as the HASG model in [41]. Therefore, technically, both the modified versions can replace the earlier developed HASG in [41], without violating operational constraints and having the same performances. Moreover, these modified versions of the models employ half of the number of transformers and their associated control and protection equipment compared with the previously developed HASG. Besides this, the modified version 2 minimises one more piece of equipment as compared to the modified version 1 by replacing the frequency converter with the BESS. Up to the best knowledge of the authors and literature surveyed, it is a novel concept introduced in this paper to replace the frequency converter with the BESS for onshore power supply. The modified version 2 looks theoretically interesting by replacing the frequency converter with the BESS, but its application is limited to the vessels having shorter duration of stay at ports and less power and energy demand as compared to the BESS capacity. However, at the moment, the modified version 2 can be expensive option for large ships with longer stay time at ports and higher power and energy demand of 60 Hz ship from 50 Hz onshore power supply or vice versa.

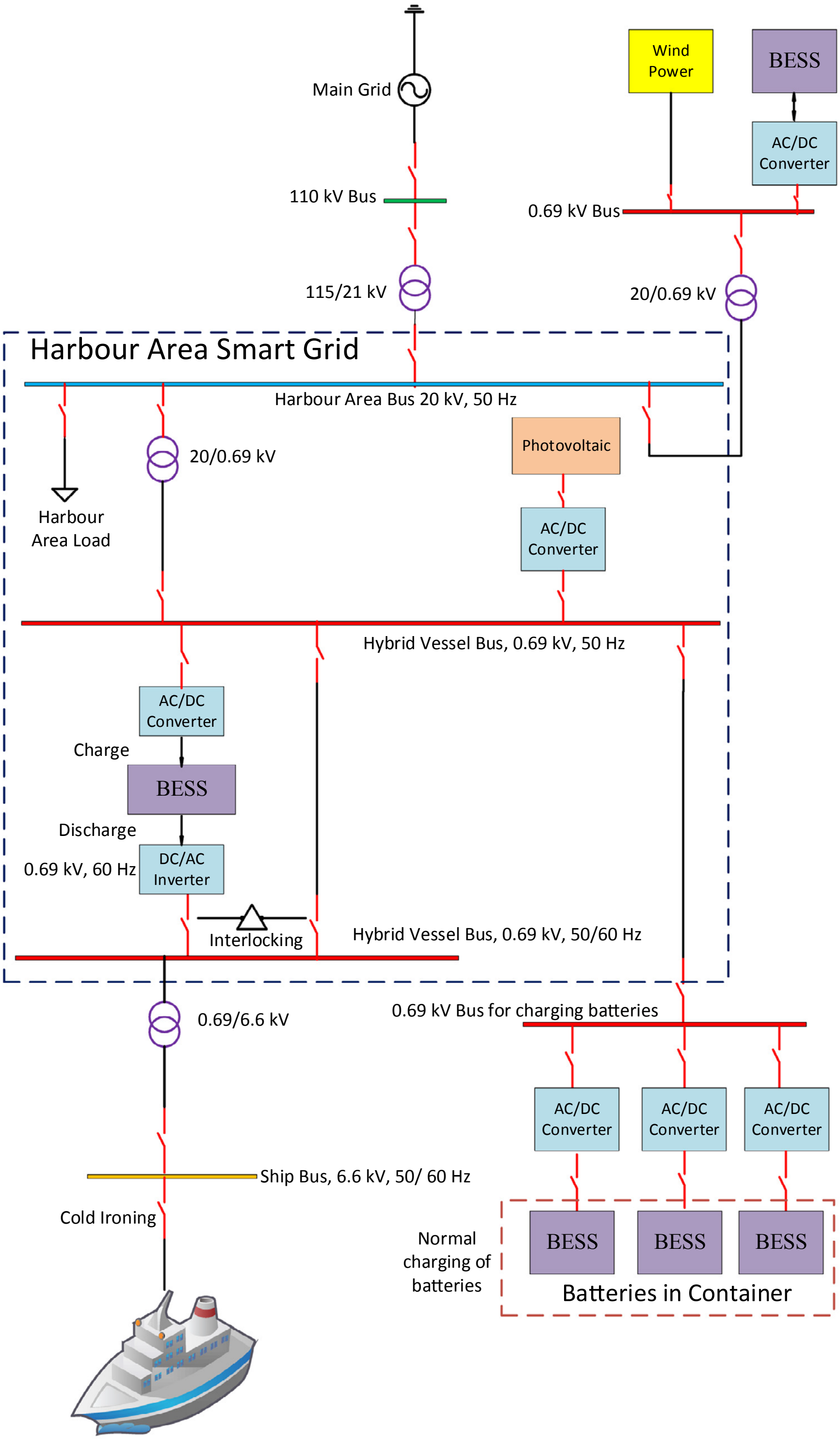

Fig. 6. Harbour Area Smart Grid modified version 2.

Nevertheless, the modified version 2 could be a future solution while considering the rapid development and decreasing prices of BESS.

The lesser the number of electrical equipment in the designed model, the lower will be the capital cost as well as losses, and more economical the solutions will be. The economic analysis of the proposed models could be an interesting task, however, it is beyond the scope of this paper, and left for future research work. In future, the modular-based harbour grid models can be designed depending on power requirements of one port, and can be then extended for other ports depending on its power requirements. The hybrid microgrid consisting of AC and DC microgrids inside the HASG can be a future solution to balance the power among different sources and loads optimally and efficiently.

5. Conclusion

The international consciousness regarding shipping air pollution, affected health of inhabitants near harbours, and phasing out fossil fuel are the driving forces for the sustainable solutions for the vessels and harbour grids. The various EU standards, directives, policies, IMO reports, and other notable organisations aim at reducing emissions, saving fuel and increasing the energy efficiency of ships. These regulations and actions regarding the toxic emissions have boosted technological development, and they are changing the paradigm of the vessels from conventional fossil-fuel vessels towards the modern hybrid and electric vessels. These modern vessels will ultimately change the current paradigm of the conventional harbour grids to harbour smart grids by employing information technology, communication system, and automation along with distributed generation and battery energy storage system.

This paper is a comprehensive review of the current and future marine solutions while outlining the key features, issues, barriers, challenges and available commercial solutions of shore to ship power supply. The onshore power supply is deemed to be an appropriate solution for getting rid of emissions and making a healthy environment at harbours. This paper has also investigated some novel design models for the HASG, which can help in the development of shore to ship power supply. An innovative concept of replacing the frequency converter with a battery storage based supply for the 60 Hz vessels can be a revolutionary step in the field of shore to ship power supply. The key features of the distinctive design models proposed for the HASG are to support the vessels for cold ironing, provide a facility for charging the batteries, and employing the renewables and battery storage at harbours. Each proposed design model in this paper can be suitable for a particular case depending upon technical requirements of the ships, the space, and infrastructure available on ports.

In spite of many advantages of employing onshore power supply, only a few of the ports are getting benefit from it because of not having any strict regulations and appropriate business models. Shore to ship power technology can advance rapidly if all the stakeholders, namely ship owners, terminal operators, port administrators, researchers, policymakers and local governments involve simultaneously for making suitable business models for promoting it. The authors believe that future research and development will be towards developing hybrid and electric vessels, safe operation of harbour grids in an islanded mode, application of battery storages both at onboard and onshore, real-time monitoring and measurement of the different parameters of the vessels. Therefore, this research is envisaged to serve as a basis for future studies and further development of the HASG.

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Design and Analysis of New Harbour Grid Models to Facilitate Multiple Scenarios of Battery Charging and Onshore Supply for Modern Vessels

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Abstract: The main objective of this study is to develop and analyse different harbour grid configurations that can facilitate the charging of batteries for modern vessels and supply onshore power. The use of battery energy storage systems in modern hybrid or entirely electric vessels is rapidly increasing globally in order to reduce emissions, save fuel and increase energy efficiency of ships. To fully utilise their benefits, certain technical issues need to be addressed. One of the most important aspects is to explore alternative ways of charging batteries with high power capacities for modern vessels. The paper presents a comprehensive overview of battery-charging configurations and discusses the technical challenges of each design from the perspective of their practical implementation, both onshore and onboard a vessel. It is found that the proposed models are suitable for vessels operating either entirely on battery storage or having it integrated into the onboard power system. Moreover, the proposed charging models in a harbour area can solve the problem of charging batteries for future hybrid and electric vessels and can open new business opportunities for ship owners and port administrators. The performance of the proposed models is validated by simulating two case studies in PSCAD: slow charging (based onshore) and fast charging (based onboard).

Keywords: Battery charging; Battery energy storage system; Emissions; Harbour grid; Onshore power supply; Ship

1. Introduction

Maritime shipping is the most common form of global trade, but it is searching for solutions to cope with the key challenges of stringent environmental air pollution, increasing energy efficiency, and independence from fossil fuels [1–6]. Moreover, electrification in the transportation sector will incorporate carbon-free electricity generation from renewables and from sustainable energy sources such as wind and solar [7,8]. The stricter emission rules set by the International Maritime Organisation (IMO) [1] and the EU Directive 2005/33/EC [9] are forcing ships to use cleaner fuels and sustainable energy sources for manoeuvring as well as during their stay at berth. The main contributors to emission footprints and overall energy efficiency of vessels are the power supply system and energy conversion systems being employed onboard the vessel. In this respect, the future development of shipping technology will be towards converting from conventional fossil-fuel-based vessel power systems to new build or retrofitted elements using renewable, sustainable, energy-efficient, less polluting and more cost-effective energy resources [10]. The life cycle assessment of new build and retrofitted marine power systems reveals that they consume less fuel (8.28 and 29.7% less, respectively) and produce lower emissions (5.2–16.6% and 29.7–55.5% less, respectively), compared to the marine power system of a conventional vessel used as a reference [11].

The history of the development of ship electrical systems is presented in [12], which notes that solid-state power electronics technology opened a new era, leading to the marine vessels known as all-electric ships (AESs). Shipboard power systems have developed from thermal to electrochemical, stored and hybrid power systems [4,13]. The modern AES has an integrated power system consisting of several generators including renewable sources and energy storage; it behaves like an islanded microgrid with a power capacity of up to 100 MW [14–22]. The AES is believed to be the most efficient ship, replacing the conventional mechanical drive system with electric propulsion. The AES concept has become the standard for large cruise ships, adopted by the major shipyards in the world [19], and is also applied on shuttle tankers, ferries and other special types of vessels [20]. Battery energy storage systems (BESSs) can play a significant role in the hybrid power system of vessels, serving various purposes such as increasing energy efficiency, improving dynamic performance, peak shaving and spinning reserve [16,23–26]. BESSs for marine applications should have a high energy density and a large discharge time, combined with the characteristic of a flat voltage-drop curve versus time [25,27]. Lithium-ion batteries are a well-established technology, having high efficiency, high power and high energy density [28,29]; these characteristics make their use feasible for electric vehicles [27,30] and for several types of ships in the marine industry [18,23,26]. Moreover, the flexible charging patterns can be used for the smart charging systems of BESSs to enable higher penetration of renewable energy resources [31,32].

An existing conventional vessel can be converted to either a hybrid vessel, by integrating a BESS with diesel generators, or to an electric vessel, by replacing the diesel generator entirely with a BESS [33]. As examples, a sailing boat [34] in an Italian harbour is likely to replace a diesel generator with a BESS along with renewable sources in the vessels. A hybrid green ship (PV/diesel) [35] in the island of Geoje, South Korea shows there is a viable option of retrofitting photovoltaic generation and a BESS alongside the diesel engine of a ship. Broadly, it has been observed that the number of battery-operated vessels has increased greatly during the last five years [36]. Shipping technology has progressed very rapidly, mainly in the areas of propulsion and power supply topologies [37]. In the coming few years, research and development in multiple technologies such as BESS, power electronics and information technology can open a modern era for vessels by employing wireless charging of batteries [38], as well as real-time measurement and monitoring of the fundamental ship parameters [12].

Modern vessels with small power capacities that operate entirely on a BESS are known as electric vessels, whereas large ships employing integrated power systems including BESSs are called hybrid vessels. Hybrid vessels can reduce fuel consumption and emissions by approximately 10–35% using advanced control strategies [13] and optimal operation of electric power generation for minimising cost by employing BESSs [5,26]. Before the development of integrated power systems for vessels, it was not possible to gain the full potential of electric ship technology [39]. Moreover, research shows that integrating emerging technologies such as photovoltaic systems and BESSs with cold-ironing practices and with the existing marine power plants can significantly reduce contributions to global warming, human toxicity, acidification and eutrophication by around 4–7 orders of magnitude; in addition, it will reduce fuel consumption and increase overall performance [40]. These modern vessels will require charging stations in ports for frequent recharge of battery storage. Therefore, the harbour area grid must be designed to accommodate charging of batteries, especially for hybrid and electric vessels, in addition to cold-ironing [10,33]. The process of shutting down auxiliary diesel engines of ships and obtaining an onshore power supply for the ships' auxiliary services during a stay in port is historically termed 'cold-ironing' or 'onshore power supply' or 'shore-to-ship power' [6,33,34,41]. The current high-voltage shore connection (HVSC) standard [42] has been developed and unanimously adopted by world leading organisations, namely the IEC, ISO and IEEE, for promoting shore-to-ship power supply.

Shore-to-ship power supply is an emerging paradigm [43], and the use of energy storage at harbours can reduce air emissions as well as facilitate the power generation with respect to optimal loading [44].

A BESS employed by modern vessels needs to be recharged after reaching a certain depth of discharge. Although the concept of the harbour area smart grid (HASG) [33] facilitates the charging of batteries for vessels in addition to supplying shore-to-ship power, a detailed analysis of charging methodologies and alternative charging scenarios has not been provided yet. A review of the literature [10,24,26,33,36,41,44] leads to the following research questions:

- What are the suitable options for charging the batteries for the vessels?
- What are the key features and technical challenges of alternative methods for charging the batteries?
- How can these different charging scenarios be applied practically?

The main objective of this study is to address the above questions by presenting new harbour grid models that incorporate various battery-charging scenarios with shore-to-ship power supply. Among these charging configurations, the two most popular (slow and fast charging) are investigated in this study, based on discussions with marine industry experts. Their feasibility and performance are validated by PSCAD simulations. The results show that the performance of these models is quite satisfactory and can be practically implemented.

The rest of this paper is organised as follows. Section 2 focuses on battery-charging methods. In Section 3, alternative ways of charging the batteries and supplying onshore power are explained in detail along with the key characteristics and technical challenges of implementing each scenario. Section 4 presents the results and monitors the performance and validity in two case studies. Section 5 discusses the key findings of the research and Section 6 concludes with the key features of each scenario along with future research directions.

2. Charging Methods

The charging methods for batteries can be divided into two broad categories, according to the time required; these are designated slow and fast charging. Slow charging of batteries is usually done in 8 h or more, while fast charging is accomplished within 1 h or less. However, these times depend on how fast the charging is required for a particular vessel type and its stay time at a particular harbour. In this paper, the fast charging time of 2 h is considered, which is typical for large cruise ships with regular routes connecting major cities in the Baltic Sea. In general, charging at such a high rate and with such a high voltage is not permitted because it may cause overcharging and overheating of the batteries beyond allowed limits, consequently reducing the battery life and possibly causing premature failure. The basic requirement to charge a battery is to connect a DC current source of a voltage higher than the open circuit voltage of the battery. AC ripple in the charging voltage and current should be kept below 4 and 5%, respectively, to avoid potential temperature rise (as recommended by battery manufacturers [45]); however, AC ripple added to DC voltage and current has no significant effect on battery life [46].

Many different charging methods and algorithms have been proposed, which greatly depend upon the type of battery and its chemistry; their aims are to improve charging time, efficiency and cycle life. These methods include single- and multirate constant current, constant current–constant voltage, double-loop control, fuzzy logic control, boost charge and pulse charge [45,47]. The most recommended and most popular method for both lithium-ion and lead-acid batteries is constant current–constant voltage (CC/CV) charging [45,47,48]. The sequence of CC/CV charging is divided into four stages [48]: trickle charge, constant current, constant voltage and charge termination. Trickle charge is used to restore deeply depleted batteries until a certain voltage threshold (80% of nominal voltage) is reached. After trickle charge, the batteries are charged with a constant current of 0.1–1 C (10–100% of rated current) depending on whether slow or fast charging is required. With constant-current charging at some selected rate, the battery voltage and charger voltage increase gradually until a maximum battery voltage (115% of nominal voltage) is reached. In constant-current charging of lithium-ion batteries, a current higher than 1 C should be avoided because it does not decrease the total charging time, but rather results in an overvoltage [48]. After reaching a voltage corresponding to 90–95% state-of-charge (SOC), the charging rate is either decreased to 0.02–0.07 C or the charging process is completely terminated. Lead-acid batteries are kept on trickle charge before charge termination [45]; however, for lithium-ion batteries, trickle charge before termination is not recommended because it can cause plating of metallic lithium, resulting in sudden disassembly of the battery [48].

In this work, simulation models of the chargers created with PSCAD software have been designed to provide a constant current of 0.1 C for 10 h of slow charging and a constant current of 0.5 C for 2 h of fast charging. These C rates provide a constant current of 290 A for offboard slow charging and 1450 A for onboard fast charging, for a set of three 2 MWh BESSs charged to a voltage of 0.69 kV; this configuration meets the standard requirements for low-voltage shore connection at ports [49]. In both slow- and fast-charging methods, the chargers are capable of providing the required DC voltage and current for charging batteries at any particular initial state-of-charge. Moreover, the SOC is typically estimated using model-based estimators [50–52]; however, in this paper it is considered by using terminal voltage. The nominal voltage selected for a 2 MWh battery is 0.6 kV and the battery achieves a maximum voltage of 0.69 kV at 100% SOC. Although the constant current–constant voltage method is recommended for batteries, only the constant-current stage (leading to a specified SOC) was simulated in our model because of limited simulation/computation time with the PSCAD software. Because charging rates of less than 1 C are recommended and therefore adopted for this study, it is assumed that there will be no temperature rise or overvoltage that will cause a major effect on the life cycle of the batteries. The chargers are modelled in PSCAD using a detailed type configuration of a three-phase AC–DC converter followed by a DC link, and high-frequency, transformer-isolated DC–DC converter to control the charging current.

3. Analysis of Multiple Battery-Charging Scenarios and Onshore Power Supply

This section discusses alternative ways of charging the batteries in addition to supplying shore-to-ship power and follows the concept of the HASG. Although the concept of the HASG has already been presented in [33], here it has been modified to take into account the realistic dimensions of components in use at harbours, such as the size and length of cables, ratings of transformers and other equipment. We keep in mind that an actual harbour area grid can benefit from any of the multiple charging station configurations. This research work has focused on multiple ways of charging batteries, either onshore or onboard (i.e., onboard a vessel), along with provision of an onshore power supply. Therefore, details of the main power supply for the harbour and the HASG are not discussed here, but onshore and onboard power systems, a comparison of different configurations and some of the key technical challenges are explained in detail. Moreover, these multiple battery-charging scenarios and onshore power supply should comply with the standard safety precautions [42,49].

Figure 1 shows a classification into the three main charging scenarios of onshore (slow charging), onboard (fast charging) and a hybrid (slow and fast charging) category, with a further breakdown into five configurations (A, B, C, D and E), with the relevant subsection in this paper noted.

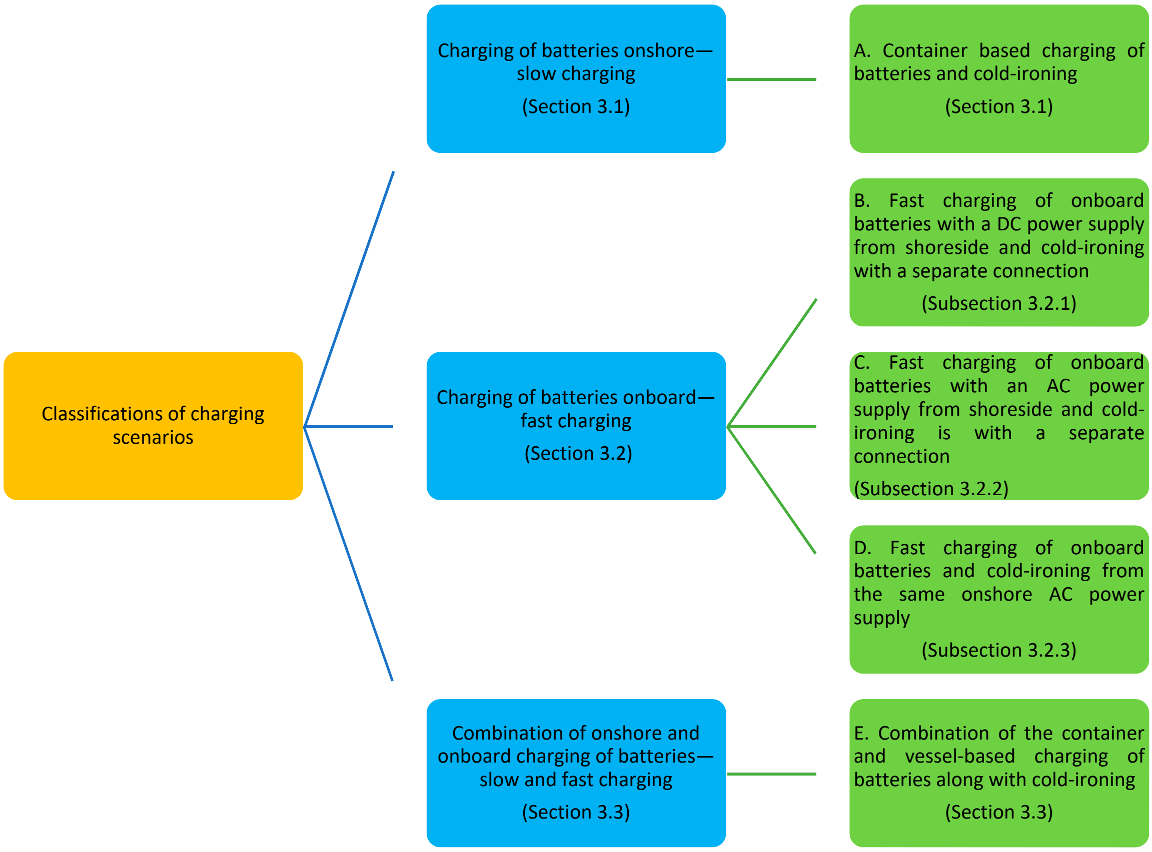

Figure 1. Classification of charging scenarios: onshore (slow), onboard (fast) and a hybrid (slow and fast).

3.1. Charging of Batteries Onshore—Slow Charging

Configuration A is shown in Figure 2. Our example shows three batteries, each of 2 MWh capacity, inside three separate containers at shoreside in the harbour area. The cold-ironing load is supplied at 6.6 kV from the onshore bus, which is fed from the 0.69 kV port bus (in the HASG) through a step-up transformer (T5). The 20 kV harbour area bus (in the HASG) supplies power to the 0.69 kV charger bus for charging batteries through a step-down transformer (T6). Power electronic converters convert 0.69 kV AC to 0.69 kV DC (maximum) on shoreside for charging the batteries in the containers. Each battery (0.6 kV nominal voltage) is charged with a constant current of 290 A DC, creating a rise in battery voltage that depends on its state of charge (SOC); the maximum is 0.69 kV DC voltage at 100% SOC. The batteries are charged within 10 h, which is considered as normal or slow charging. The discharged batteries (from vessel) are exchanged with charged ones (from containers at shoreside) during cold-ironing. A main feature of this configuration is that the batteries may be charged in off-peak times at lower cost and less power requirement in comparison with other configurations.

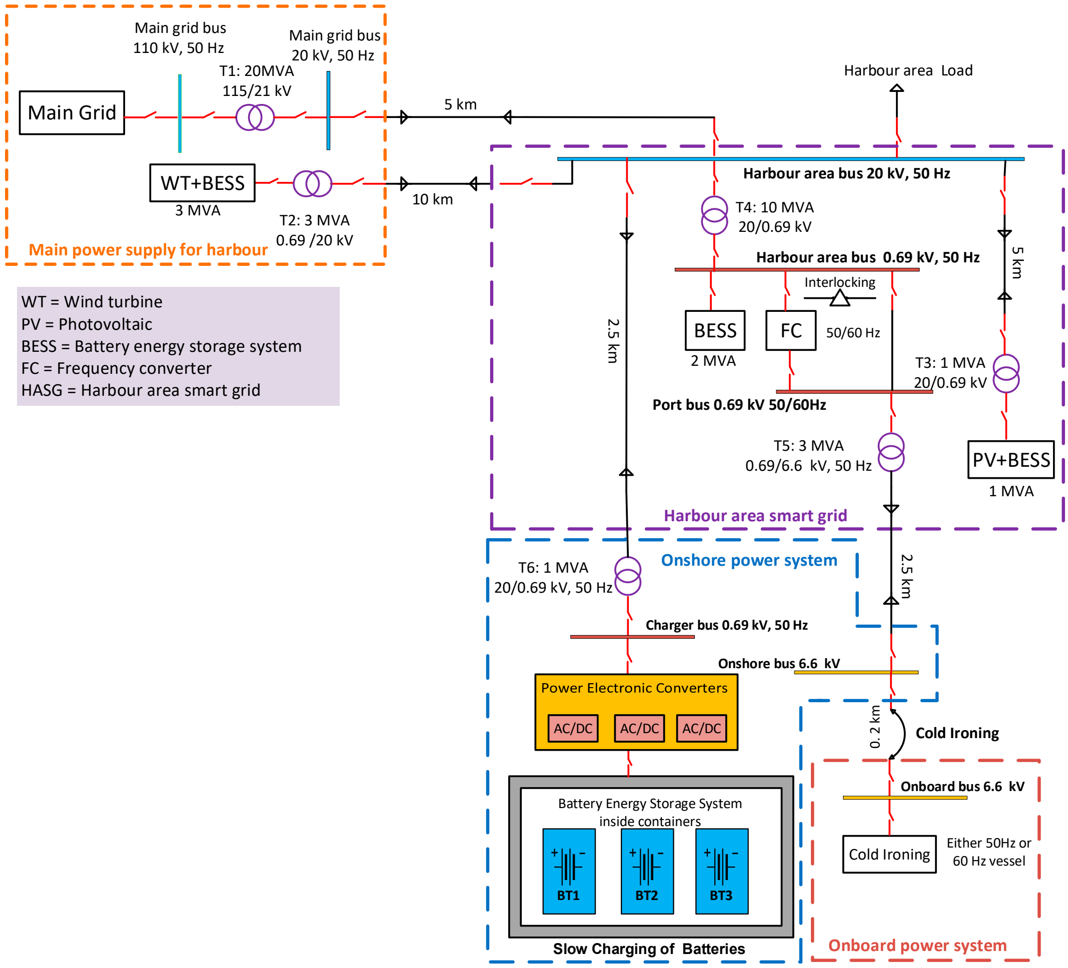

Figure 2. Configuration A: Container-based charging of batteries and cold-ironing.

3.2. Charging of Batteries Onboard—Fast Charging

In our examples of vessel-based charging methodologies, the vessel has three onboard fixed batteries, each of 2 MWh capacity. Each battery (0.6 kV nominal voltage) is charged with a constant current of 1450 A DC, producing a variable voltage (depending on the SOC of battery) to a maximum of 0.69 kV DC at 100% SOC. The batteries are charged within 2 h in a fast-charging mode during the vessel's stay in harbour. We consider three configurations for fast charging, which vary in the power supply layout for cold-ironing and the battery-charging connections to the vessel. However, the charging methodology applied is the same in the following three configurations.

3.2.1. Charging of Batteries with DC Power from Shoreside and a Separately Connected AC Onshore Power Supply

This is configuration B, where the AC onshore power supply and DC power for charging the batteries are supplied separately; these originate in the 0.69 kV port bus and 20 kV harbour area bus, respectively. Transformer (T6) converts power from the 20 kV harbour area bus to 0.69 kV AC, which power electronic converters transform to 0.69 kV DC (maximum) for charging batteries onboard, as shown in Figure 3. This configuration is distinguished by the availability of DC power supply at shoreside, which simplifies charging by eliminating the conversion of AC to DC power onboard. Thus, only DC–DC power electronic converters onboard the vessel are needed to control the charging voltage.

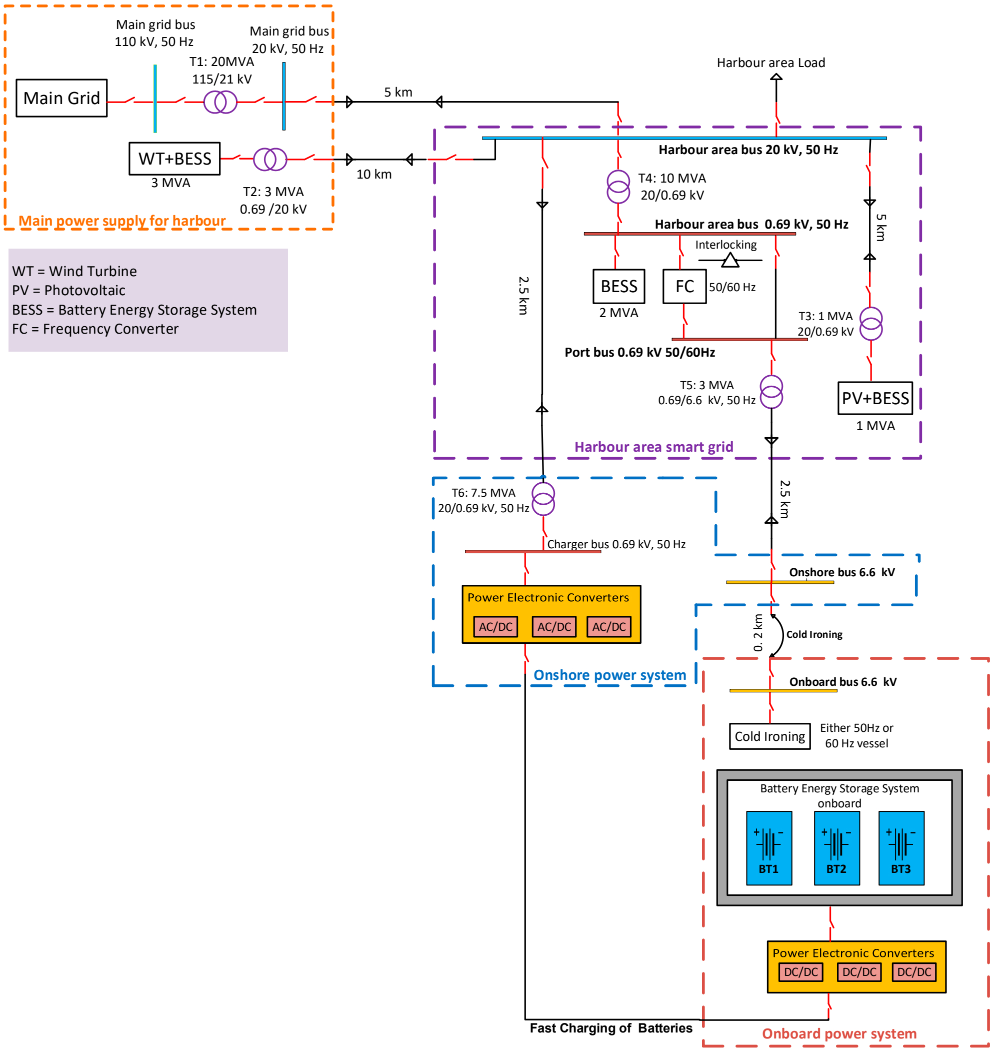

Figure 3. Configuration B: Fast charging of onboard batteries with a DC power supply from shoreside and cold-ironing with a separate connection.

3.2.2. Charging of Batteries with a Shoreside AC Power Supply and a Separately Connected Onshore Power Supply

In configuration C (Figure 4), separate AC connections for the cold-ironing load and for charging the batteries are supplied power from the 0.69 kV port bus and the 20 kV harbour area bus, respectively. The 20 kV to 0.69 kV step-down transformer (T6) and the power electronic converters (0.69 kV AC to 0.69 kV DC maximum) for charging batteries are placed onboard. This configuration saves space at harbour areas because it does not require any charging-related equipment onshore, which is the key feature of the configuration.

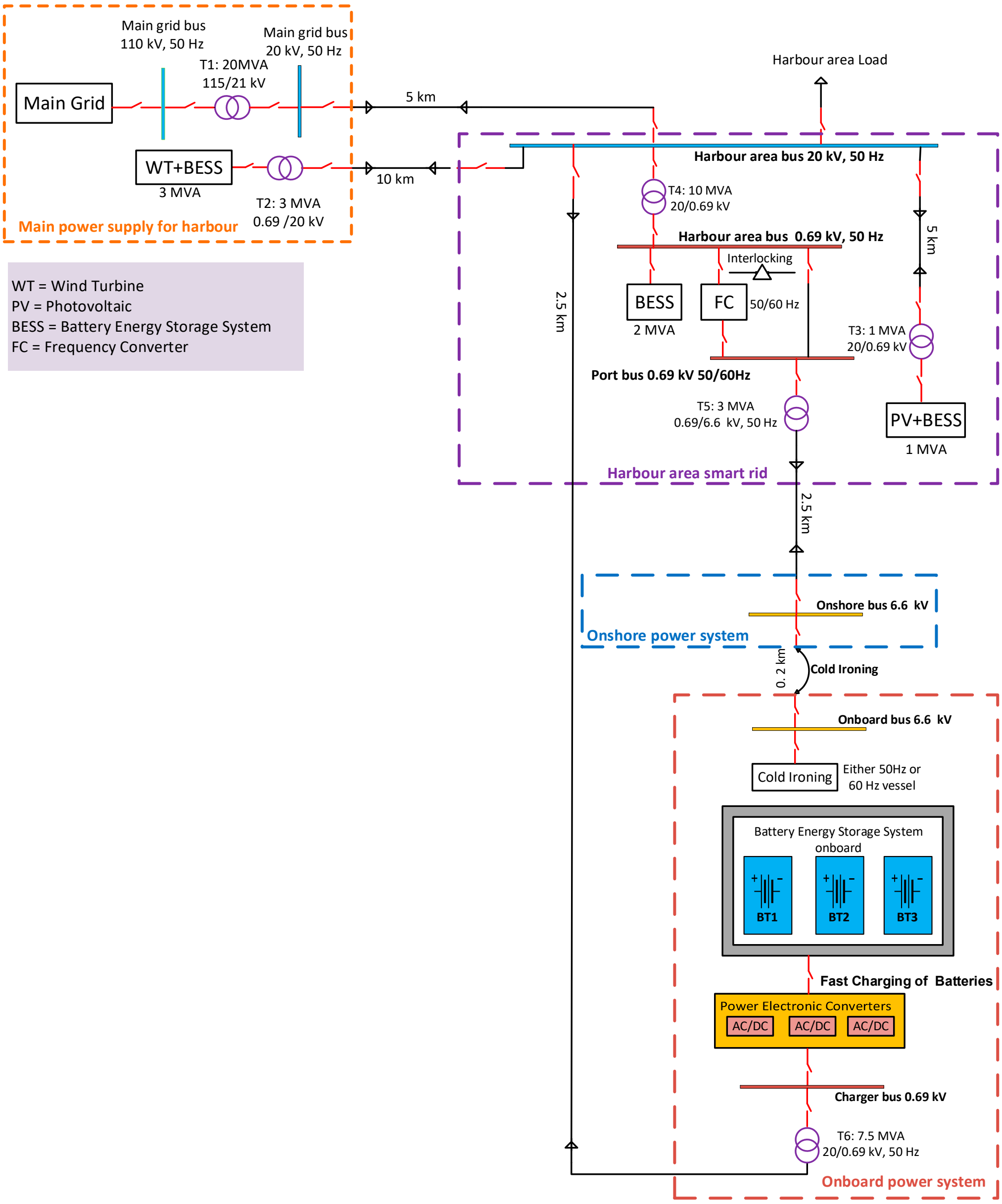

Figure 4. Configuration C: Fast charging of onboard batteries with an AC power supply from shoreside and onshore power is with a separate connection.

3.2.3. Charging of Batteries and Onshore Power Supply with Same AC Power Supply

In configuration D (Figure 5), power is supplied by a single 6.6 kV connection (from the harbour area bus, 0.69 kV, 50 Hz) through a step-up transformer (T5, in the HASG) for both cold-ironing and onboard battery charging. Transformer (T6) steps down the onboard 6.6 kV to 0.69 kV AC, which is converted to 0.69 kV DC (maximum) for charging batteries.

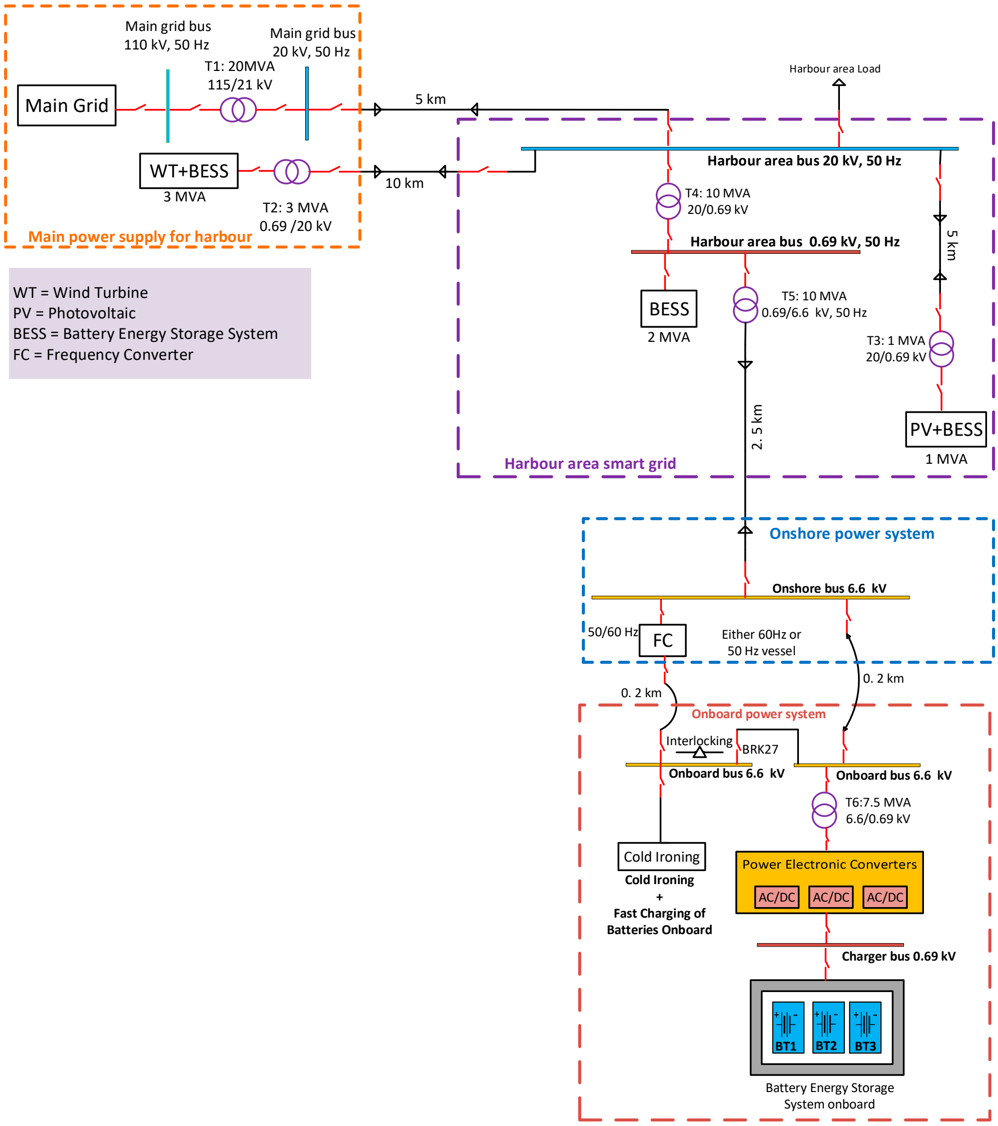

Figure 5. Configuration D: Fast charging of onboard batteries and cold-ironing from the same onshore AC power supply.

The major difference between this charging configuration and the others is the location of the frequency converter. The harbour grid is initially assumed to be at 50 Hz (Figure 2), and the frequency converter shown has a power capacity that is only sufficient for the 60 Hz cold-ironing load; it is therefore not possible to include battery charging, using a single power supply connection coming through the frequency converter. The alternative of increasing the power capacity of the frequency converter to accommodate both types of load is not economically feasible because the frequency converter is one of the most expensive pieces of equipment in the harbour grid.

In configuration D, the frequency converter has been moved from a location connecting the harbour bus to the port bus (Figure 2) to a location between the onshore bus and the onboard vessel power system (Figure 5). Consequently, the port bus and its corresponding switchgear and protection devices are no longer required. The interlocking switch is placed to allow for either a 50 Hz or 60 Hz power supply for the cold-ironing load; however, this configuration can supply both cold-ironing load and battery-charging load with a single connection only if the harbour grid and the vessel power requirements are at the same power frequency, otherwise separate connections are required.

3.3. Combination of Onshore and Onboard Charging of Batteries—Slow and Fast Charging

Configuration E is a combination of container-based and vessel-based batteries (Figure 6). It consists of three batteries in containers at shoreside as well as three fixed batteries in the vessels, each of 0.6 kV nominal voltage and 2 MWh capacity. In this configuration, transformer (T6) steps down 20 kV to 0.69 kV AC, which power electronic converters convert to 0.69 kV DC (maximum) for charging the batteries in the shoreside containers. The shoreside batteries are charged with a constant current of 290 A DC to a maximum voltage of 0.69 kV DC at 100% SOC. The shoreside batteries are charged within 10 h, considered as slow charging; however, the fixed vessel batteries are then charged from shoreside batteries within 2 h in a fast-charging mode during the vessel's stay at the harbour. The fast charging is with a constant current of 1450 A DC to a maximum of 0.69 kV DC at 100% SOC of the battery. This configuration may be characterised as a dual-charging mode that contains slow as well as fast segments.

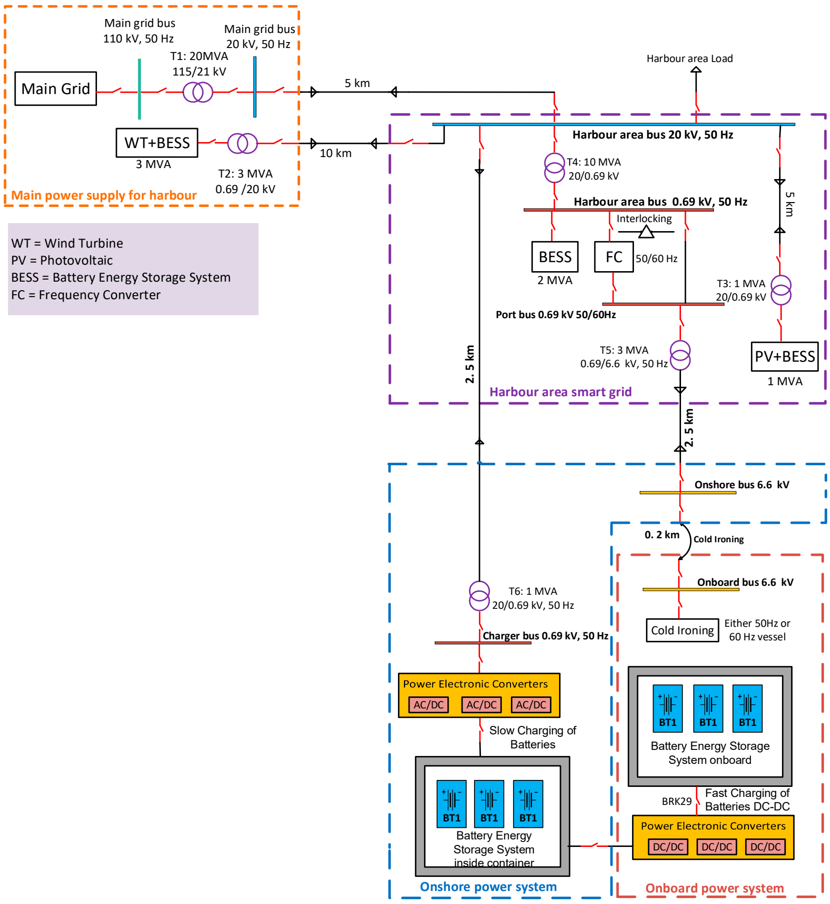

Figure 6. Configuration E: Combination of the container- and vessel-based charging of batteries along with cold-ironing.

3.4. Characteristics of Main Charging Scenarios

A comparison of the scenarios is presented in Table 1, using the classifications given in Figure 1.

Table 1. Attributes of the charging configurations.

Charging Scenarios	Advantages	Disadvantages
Charging of batteries onshore—slow charging Configuration A	Easy and flexible to implement. Low power required at shoreside with the slow/normal charging of batteries at shoreside as compared to all other configurations. Power cables, power electronic converters, chargers, switchgear and protection equipment for charging system will be of lower power capacity than the other configurations. Simple chargers are required and should not result in battery overheating.	Equipment and personnel required to move the battery containers. Higher capital cost because every harbour should have a sufficient number/capacity of batteries in containers to replace those in vessels being serviced. No space saving at the harbour area. Higher system downtime due to connecting/disconnecting of batteries; mechanical failure can occur.
Charging of batteries onboard—fast charging Configurations B, C, D	Lower capital cost for batteries than configurations A and E: batteries remain onboard, with no exchange of discharged/charged batteries. Less space is required on shoreside as compared to configurations A and E. No equipment required to move battery containers as compared to configuration A.	Higher power required on shoreside as compared to configurations A and E. Power cables, converters, chargers, switchgear and protection equipment for charging system will be of higher power capacity than for configurations A or E. As the charging rate increases, the danger of overcharging and overheating also increases. Higher energy density batteries and compact onboard chargers are needed. More space and weight onboard the vessel are required in configurations C and D for the extra transformer on the vessel for charging the batteries. Transformer onboard poses a risk of fire so that physical isolation may be required.
Combination of onshore and onboard charging of batteries—slow and fast charging Configuration E	Lower power required at shoreside than configurations B, C and D. Power cables, power electronic converters, chargers, switchgear and protection equipment for charging system on shoreside will be of lower power capacity than for configurations B, C and D. No equipment required to move battery containers as compared to configuration A. This configuration may be suitable if a hybrid microgrid with AC and DC buses is designed.	Configuration E has almost the same disadvantages as configuration A, except there is no need for equipment to move battery containers and no risk from connecting/disconnecting of batteries. Configuration E has more or less the same disadvantages as those of fast charging configurations (B, C and D) excluding the need for transformer onboard.

3.5. Technical Challenges of Charging Scenarios

The first charging scenario (configuration A), which is container-based, requires at least the same number/capacity of replacement batteries in containers as the number/capacity onboard the vessel being serviced, as the discharged and charged batteries are exchanged during the vessel's stay in harbour during cold-ironing. This increases the capital cost for batteries, requires additional equipment to move the battery containers, causes a higher system downtime from the connecting/disconnecting of batteries and increases the risk of mechanical failure. Moreover, this configuration needs shoreside space for charging the batteries inside containers.

The second charging scenario, onboard-based charging of batteries in configuration B, C or D requires higher power levels from shoreside than configurations A and E as a result of the fast charging of batteries directly from the grid supply. The power cables, power electronic converters, chargers, switchgear and protection equipment for a charging system in the vessel-based configurations will be of higher power capacity than configuration A, and thus require higher capital cost for the equipment and for advanced control and safety measures. Moreover, with the higher charging rate during fast charging, the danger of overcharging and overheating is increased. The transformer onboard the vessel in configurations C and D may pose the risk of fire, requiring an arrangement providing physical isolation. Configuration C requires two high-voltage plug connections, requiring personnel with a high-voltage certificate, and can thus incur additional costs compared with other configurations. Configuration D requires a different location for the frequency converter than in all the other configurations, otherwise a higher power capacity frequency converter with higher cost is needed.

The third charging scenario, configuration E, has both slow- and fast-charging characteristics, and requires two types of power supply equipment (such as power electronic converters, power cables, chargers, switchgear and protection devices) with low and high power ratings, respectively. Thus, on one hand, configuration E is expensive, and in addition, it produces higher power losses due to dual power conversion stages. However, configuration E is a suitable design when considering a hybrid microgrid consisting of AC and DC buses inside the HASG, that is, a harbour having the potential of using renewable and sustainable energy sources, and where there is availability of space for the required infrastructure.

4. Simulation Study

In order to verify the technical feasibility of these configurations, a simulation study was carried out. All the configurations were modelled with PSCAD software, and the components were dimensioned to provide reasonable results. Both slow- and fast-charging scenarios were used for simulations (e.g., the container-based charging of batteries (configuration A) and the vessel-based charging of batteries (configuration D)). A time-varying dynamic load of 2 MW maximum power was considered for cold-ironing in both the slow- and fast-charging simulation models. The nominal charging load including power losses in configuration A was 0.7 MW for a charging rate of 0.1 C, whereas in configuration D, the load was 4.5 MW for a rate of 0.5 C.

Tables 2 and 3 present the simulation results of container-based and vessel-based charging of batteries, respectively. The onshore bus voltage is maintained within specified limits (a maximum voltage drop of 3.5%, according to the HVSC standards) during maximum cold-ironing load. The battery voltage at a specific SOC and battery current is also maintained within the required nominal values. The frequency of the onshore power supply is constant, and the total harmonic distortion (THD) of the charger current and voltage are within limits. The rate of change of the SOC for slow and fast charging is indicated in Figure 7, which is based on the sampled values of 20 seconds while considering the initial SOC at 25, 50 and 75%. This shows that these chargers are capable of charging the batteries in the assumed time frames of 10 and 2 h, respectively. Moreover, in Figure 7, the fast-charging rate is five times higher than the slow rate.

Table 2. Simulation results of Configuration A: Container-based charging of batteries and cold-ironing.

Entities	Nominal Values	Measured Values
Main Grid Voltage	110 kV	110 kV (Constant)
Main Grid Voltage	20 kV	20.88 kV (Maximum)
Harbour Bus Voltage	20 kV	21.15 kV (Maximum)
Harbour Bus Voltage	0.69 kV	0.72–0.74 kV
Port Bus Voltage	0.69 kV	0.71–0.74 kV
Onshore Bus Voltage	6.6 kV	6.4–7.1 kV
Battery Voltage	0.6 kV	0.678 kV (at 95% SOC)
Battery Current	290 A	290 A
Onshore Bus Frequency	50 Hz	50 Hz
THD for Charger Current (%)	5 % (Maximum Allowed)	5 %
THD for Charger Voltage (%)	5 % (Maximum Allowed)	1.19 %

Table 3. Simulation results of Configuration D: Fast charging of onboard batteries and cold-ironing from the same onshore AC power supply.

Entities	Nominal Values	Measured Values
Main Grid Voltage	110 kV	110 kV (Constant)
Main Grid Voltage	20 kV	21.9 kV (Maximum)
Harbour Bus Voltage	20 kV	21.7 kV (Maximum)
Harbour Bus Voltage	0.69 kV	0.71–0.72 kV
Port Bus Voltage	0.69 kV	0.66–0.69 kV
Onshore Bus Voltage	6.6 kV	6.45–6.75 kV
Battery Voltage	0.6 kV	0.7 kV (at 95% SOC)
Battery current	1450 A	1450 A
Onshore Bus Frequency	50 Hz	50 Hz
THD for charger current (%)	5 % (Maximum Allowed)	1.386 %
THD for charger voltage (%)	5 % (Maximum Allowed)	1.52 %

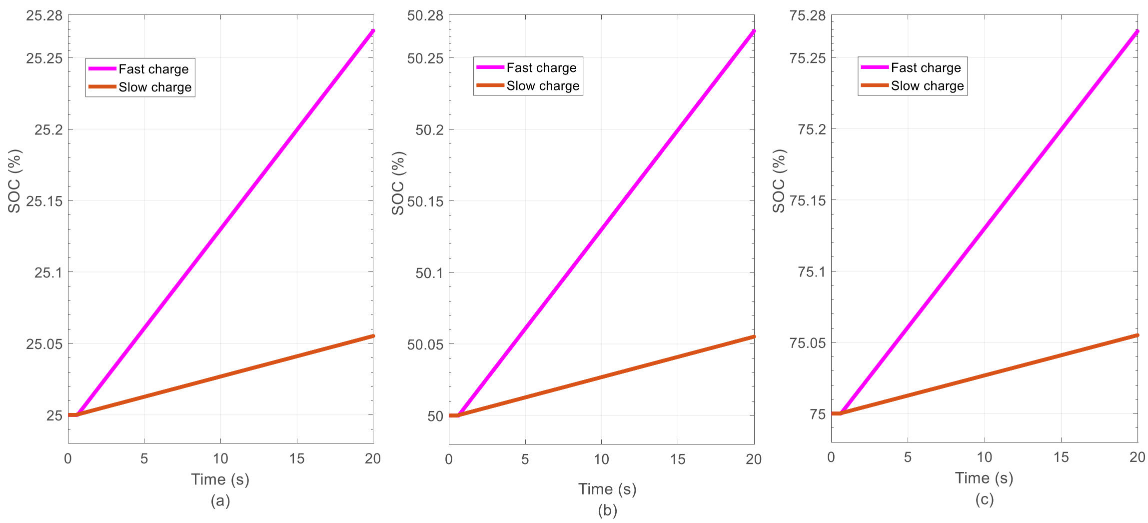

Figure 7. Rate of change of SOC of batteries in configurations A and D, (**a**) When BESS is at 25% SOC (**b**) When BESS is at 50% SOC (**c**) When BESS is at 75% SOC.

The simulation results show that the performance for slow and fast charging (configurations A and D, respectively) is satisfactory, and these configurations can be implemented practically. It is observed that maintaining all bus voltages in the slow-charging model (configuration A) is achievable as a result of the separate connections for battery charging and for the onshore supply of the cold-ironing load.

However, in the fast-charging model (see Figure 8 for a simulation of configuration D), it is challenging to maintain all bus voltages, especially for the onboard and charging buses. The dynamic changes of the voltage and power in the onboard and charger buses, resulting from time-varying cold-ironing loads together with charging, are highlighted by the dotted lines. At t = 0.6 s, the fast charger load is connected, and momentary rapid changes in voltages occur due to switching transients. To observe the dynamics, a time-varying cold-ironing load is taken into account by assuming power capacity of certain ports. The cold-ironing load is connected initially with a power rating of (1 MW + j0.15 MVAr), decreased to (0.5 MW + j0.075 MVAr) at t = 5 s, increased to a maximum load (2 MW + j0.3 MVAr) at t = 10 s and finally disconnected at t = 18 s. This shows that reactive power flow in the charger bus depends on the onboard bus voltage; this flow decreases along with a decrease in onboard bus voltage due to an increase in the cold-ironing load. Simulation shows that the voltage on the onboard and charger buses also drops during high power conversion (for charging) alone. There are several options for maintaining the voltage, but an on-load tap changer on transformer T1 is considered a suitable and economic solution and it is used in this study to maintain the voltage whenever the downstream voltage at the onshore and onboard buses varies due to the dynamic load.

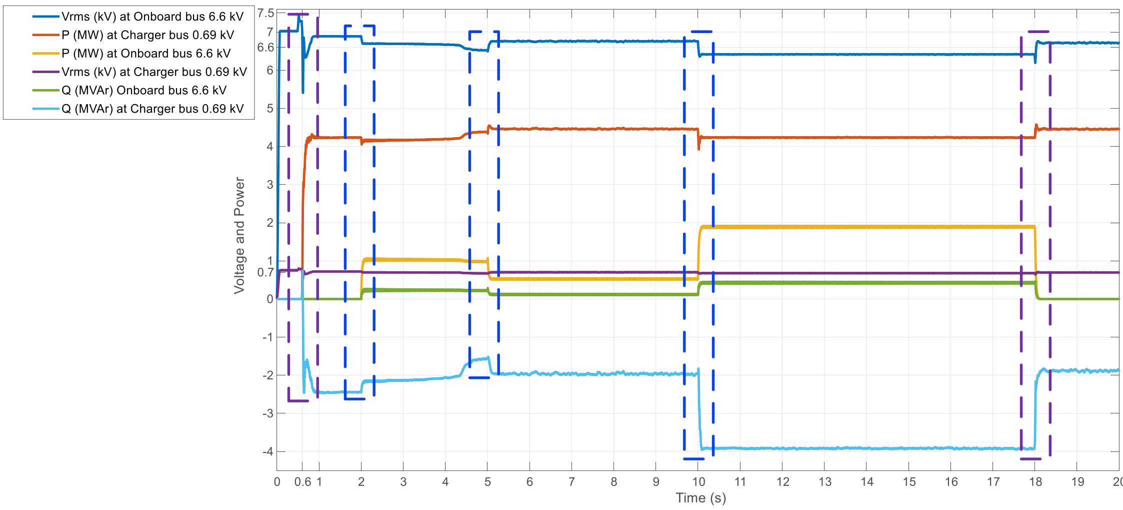

Figure 8. Voltage and power at onboard and charger buses in configuration D.

5. Discussion

The findings reveal that BESSs can play a significant role in the onboard and onshore marine sectors as a result of several beneficial features. The application of BESSs onboard a vessel can increase the operational life of diesel generators and reduce their maintenance cost. It can also improve the dynamic response to varying propulsion loads by providing peak load power instantly and store energy during low load power requirements. As a part of a shipboard power system, a BESS can also save fossil fuels and increase energy efficiency in modern hybrid vessels. At the same time, the application of a BESS in a modern HASG can enable the use of renewable energy sources at shoreside in harbour areas and support a weak grid in the case of power unbalance, stability and reliability issues. A BESS in harbour areas can also be used as an energy management system to optimally and efficiently control energy flows between the BESS and the main grid for the purpose of energy arbitrage and peak shaving. Moreover, in the islanded mode of operation of an HASG, load shedding may not be a viable option because of the importance of keeping to the schedule of a vessel's stay at a seaport. Therefore, a BESS as a master unit can support the uninterrupted operation of an HASG.

Onboard power electronic converters (configurations C and D) that operate on both 50 and 60 Hz would enable a ship to visit any harbour grid with either of these two power supply frequencies. The two charging configurations A and D are suitable for vessels operating entirely on a BESS, or with a BESS as part of a hybrid energy system, and their performance has been validated with PSCAD simulations.

The slow-charging configuration is a feasible choice for a harbour having a low power capacity and ships with less space available onboard, and the fast-charging configuration could be preferred for a harbour with high power capacity or low docking space. However, the slow charging could be preferred because at faster charging rates, more power is lost as heat and therefore cannot be recoverable as electricity later. In future, a configuration that combines slow- and fast-charging methodologies (configuration E) would be a useful option when considering a hybrid microgrid at a harbour. It can be a costly investment, however, it has the beneficial features of both slow and fast charging. This option is suitable for harbours with a low power capacity and for vessels requiring fast charging onboard, where the availability of space onboard and on shoreside is not a major problem.

6. Conclusions and Outlook

This study was conducted to explore alternative configurations for battery charging in harbours for modern vessels employing BESSs as a key component. Based on a literature review, it is concluded that this is the first attempt to systematically investigate these alternatives. Several configurations for battery charging in harbours were investigated, and each configuration has its key merits and limitations from the perspectives of economic and technical feasibility, and of space availability on shore and ship. The appropriate charging configuration can be decided based on the available infrastructure at a harbour and the demands of ships.

Two charging scenarios were further developed in detail, one from the slow-charging and the other from the fast-charging category; their performance was validated by simulation studies. These two categories are applicable to both electric and hybrid vessels. The present findings can be the basis for ships' owners creating suitable business models and for port administrators promoting the application of BESSs in the marine sector.

Further research is required on hybrid microgrids for harbour areas. The hybrid microgrid can facilitate the combination of slow- and fast-charging configurations while exploiting the advantages of both types. Finally, the future work of the authors is in expanding the harbour grid system on a modular basis; advanced control techniques can be applied to operate these modules in parallel, adapted to the specific power requirements of different ships visiting the harbour area simultaneously. The other interesting future work is to investigate round-trip efficiency of battery energy storage systems which determines power lost as heat at certain charging rates.

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Abbreviations

AC	Alternating Current
AES	All-Electric Ship
BESS	Battery Energy Storage System
CC/CV	Constant Current–Constant Voltage
DC	Direct Current
EU	European Union
FC	Frequency Converter
HVSC	High-Voltage Shore Connection

HASG	Harbour Area Smart Grid
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IMO	International Maritime Organization
ISO	International Organization for Standardization
PSCAD	Power Systems Computer-Aided Design
PV	Photovoltaic
SOC	State of Charge
THD	Total Harmonic Distortion
WT	Wind Turbine

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Article

Sizing and Allocation of Battery Energy Storage Systems in Åland Islands for Large-Scale Integration of Renewables and Electric Ferry Charging Stations

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Abstract: The stringent emission rules set by international maritime organisation and European Directives force ships and harbours to constrain their environmental pollution within certain targets and enable them to employ renewable energy sources. To this end, harbour grids are shifting towards renewable energy sources to cope with the growing demand for an onshore power supply and battery-charging stations for modern ships. However, it is necessary to accurately size and locate battery energy storage systems for any operational harbour grid to compensate the fluctuating power supply from renewable energy sources as well as meet the predicted maximum load demand without expanding the power capacities of transmission lines. In this paper, the equivalent circuit battery model of nickel–cobalt–manganese-oxide chemistry has been utilised for the sizing of a lithium-ion battery energy storage system, considering all the parameters affecting its performance. A battery cell model has been developed in the Matlab/Simulink platform, and subsequently an algorithm has been developed for the design of an appropriate size of lithium-ion battery energy storage systems. The developed algorithm has been applied by considering real data of a harbour grid in the Åland Islands, and the simulation results validate that the sizes and locations of battery energy storage systems are accurate enough for the harbour grid in the Åland Islands to meet the predicted maximum load demand of multiple new electric ferry charging stations for the years 2022 and 2030. Moreover, integrating battery energy storage systems with renewables helps to increase the reliability and defer capital cost investments of upgrading the ratings of transmission lines and other electrical equipment in the Åland Islands grid.

Keywords: battery energy storage system; battery sizing; distributed generation; emissions; harbour grid; renewable energy sources

1. Introduction

Global trade proceeds to a large extent by the utilization of marine ships [1]. These marine ships can be considered as moving power plants, and their power capacity varies in the range of tens of megawatts [2]. Traditional ships mostly operate on fossil-fuels and create a significant amount of toxic emissions and air pollutions [3] during navigation and when staying at ports [4]. The international maritime organisation [1] and EU directives [5] have set targets and goals to limit environmental pollution and encourage cleaner sources of power generation for ships as well as harbours. Conventionally, an auxiliary diesel engine generates electricity for ship services while staying at harbours. However, at present, an onshore power supply/cold-ironing is a preferred solution for ships to shut down their diesel engines at harbours to fill the requirements of strict emission regulations and make ports free from greenhouse gases [5,6]. Due to environmental reasons and new emission regulations, the power systems of ships and harbours are also shifting from non-renewable to renewable-based power generation. This will lead to the increased installation of renewable energy sources (RESs) and battery energy storage systems (BESSs) at ships and harbours [7]. At present, distributed generation (DG) is used to deploy electrical energy, especially from RESs, and is available in different forms and different scales, from the micro-scale to large-scale [8]. Wind and photovoltaic energy sources are gaining prominence, especially in harbour areas, to cope with the growing demand of modern hybrid and fully electric ships and ferries requiring an onshore power supply as well as charging stations. The integration of RESs into the harbour grid can be beneficial to avoid the expansion of the existing electrical network while supplying the additional power demand [2].

The modern ships operate either fully on electricity or with hybrid solutions and require their BESSs to be charged either from shipboard power systems or harbours. The all-electric ships [9] and all-electric hybrid vessels [10] require energy saving, energy efficiency and energy management systems for their integrated shipboard power system with the application of advanced power electronic converters [11], RESs and BESSs. The operation of the shipboard power system is also critical and prone to some technical issues regarding power quality [11] and power system protections [12]; therefore, BESSs are useful to mitigate power quality and reliability issues. Alternative harbour grid configurations have been proposed for the slow and fast charging of batteries for electric/hybrid vessels [13]. Modern ships require infrastructure in ports and harbour grids to be upgraded in order to facilitate the use of electric ships, enable the participation of harbour area microgrids in electricity markets [14,15] and benefit from the Internet of Maritime Things [16]. Therefore, the concepts of smart ports [17], wise ports [18], green ports [19], zero-emissions ports [20], and harbour area smart grids [4] deal with the design, operation and control of modern ports in such a way as to encourage power generation from renewables, manage and control power flow with flexible loads, and for charging and discharging the batteries at harbours [2,15]. Moreover, modern ports are not only consumers of electricity but also prosumers [21], using local generation from renewables to store energy and supply to the main grid if needed. However, intermittent power generation from renewables is a critical issue for the reliable operation of harbour grids; therefore, BESSs play a crucial role in balancing the power generation and demand by charging and discharging whenever needed, thereby providing flexibility in the power supply [22]. In order to utilise BESS efficiently, the challenging task is to optimally design the size and location of BESSs while keeping the future integration of RESs and load demand in mind [23,24]. In this way, the locally generated electricity from RESs could balance the load demand and power supply without expanding the power capacity of the overall network. At the same time, the future harbour grids could also anticipate a liberalised energy market to supply surplus power to utilities. In order to achieve the above-mentioned goals, an appropriate size of BESSs is required to be located at certain substations near harbours so that the power required at any substation could be uninterruptedly supplied.

Although the integration of RESs and BESSs has been considered by many researchers for shipboard power systems—although very few researchers have dealt with harbour grids—as depicted in Table 1, no researchers have considered the sizing and locations of BESSs for harbour grids while considering the integration of RESs and electric ferry charging requirements. The main contribution of this paper is to develop an algorithm which defines the proper size and power capacity of BESSs for any operational harbour grid planning for integrating RESs and electric ship and ferry charging stations locally without the expansion of the power capacity of transmission lines and other grid components. To the best of the authors' knowledge, and according to the literature surveyed so far, this is the first attempt to size and allocate BESSs on larger scale for any harbour grid, planning for the integration of a huge amount of RESs. In order to examine the proposed methodology, a real-world system—the Åland Islands power system—is considered as the test case. On this basis, two future case studies are modelled in the Power Systems Computer-Aided Design (PSCAD) software, which plans a significant amount of RESs for the two horizon years of 2022 and 2030. The maximum loadings with a minimum integration of renewable power generation for the years 2022 and 2030 are taken as base cases, keeping future predictions in mind. The base cases are simulated in PSCAD without BESSs under maximum loading and minimum generation for the years 2022 and 2030. The simulation results are compared with the base case studies and validate that the batteries are accurately sized and located at a proper location to avoid the expansion of the power capacity of the transmission lines, transformers, and other protective electrical equipment in Åland's electrical network.

Table 1. Taxonomy of literature review. PV: photovoltaic; BESS: battery energy storage system.

Ref.	Year	Wind	PV	BESS	Onshore Power Supply	Battery-Charging Stations for Vessels	Port as Energy Market	Sizing of BESS	Allocation of BESS	Harbour Grid/Port Power Systems	Shipboard Power Systems
2	2019						✗	✗	✗		✗
3	2017						✗	✗	✗		✗
6	2013	✗			✗	✗	✗	✗	✗	✗	
10	2018	✗	✗		✗	✗	✗	✗	✗	✗	
12	2019						✗	✗	✗		✗
13	2019		✗	✗		✗		✗	✗		✗
14	2019	✗	✗	✗		✗		✗	✗		✗
16	2015				✗	✗		✗	✗	✗	
17	2016					✗		✗	✗		✗
19	2012					✗	✗	✗	✗		✗
20	2017		✗			✗	✗	✗	✗		✗

The rest of the paper is organised as follows. Section 2 provides insights for utilising lithium-ion (Li-ion) batteries for stationary applications, shows the importance of modelling their performance characteristics accurately, and explains the methodology of developing an algorithm for the proper sizing and location of BESSs on different substations of harbour grids considering RESs. Section 3 investigates the impacts of the proposed methodology, analyses the results for two different horizon years, and discusses the main findings and challenges in designing and allocating BESS at proper substations; finally, Section 4 presents the conclusions and future work.

2. Proposed Methodology for BESS Sizing and Allocation

Modern power systems are rapidly changing with the increased penetration of RESs and transportation electrification, including in the marine sector. Under such circumstances, BESSs play an important role in providing short-term flexibility for various stationary grid applications. It is necessary to understand and analyse the effects of such architectural changes on the stability and reliability of the grid. Considering the inherent characteristics and cost economics of BESSs, defining the role of BESSs and their sizing is essential. In this paper, a methodology is proposed for BESS sizing and allocation to mitigate line congestion (leading to capital deferral) for harbour grids. Figure 1 provides an overview of the technologies included in the study. Renewable energy sources such as photovoltaic (PV) and wind energy and the load consumption arising from ferry charging stations, residential consumption, and other related harbour loads are considered in the study. BESSs act as the main flexibility resources in the system. This section provides an overview of the characteristics and performance of Li-ion batteries, defining their capability to act as short-term flexibility resources in smart grids. It also explains the reason for accurately modelling Li-ion battery behaviour, by means of an equivalent circuit battery modelling methodology due to its highly non-linear voltage and current characteristics. This is followed by an algorithm which was developed to size and allocate BESSs for the stable operation of weak grids or harbour grids, catering for changes caused by increased renewable energy penetration and load consumption changes.

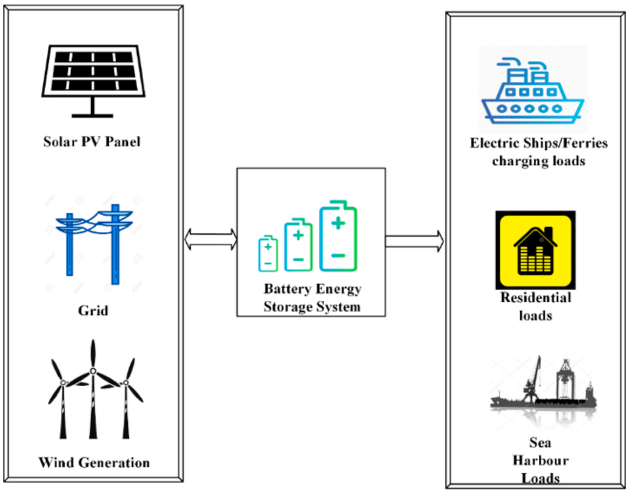


Figure 1. Technologies involved in the method.

2.1. Lithium-Ion Batteries

The large-scale integration of renewables and low-emission energy sources at all voltage levels—i.e., high, medium and low voltage—has followed a rising trend. Integrating such a large amount of variable and usually low-inertia renewable energy sources has significant impacts—predominantly voltage and frequency instabilities—compared to traditional centralized power systems. Due to these changes and effects, there is an increasing need for various type of energy storages for applications with different time-scales. For flexible energy needs, the interest in rapidly controllable Li-ion BESSs has increased due to their technological advancements and decreasing costs. The accurate modelling of battery packs for stationary energy storage grid applications has been minimal, as the majority of the literature considers battery systems as an ideal DC voltage source [25] or utilizes mathematical modelling techniques. Mathematically based kinetic battery models (KBM) were first proposed in [26] for lead-acid batteries. Modified KBMs [27] are widely used to simulate Li-ion batteries for smart grid simulations. However, KBMs fail to address the non-linear characteristics of Li-ion batteries, which are also affected by various operating conditions such as their State-of-Charge (SoC), temperature, current rate, and age.

Physics-based electrochemical models [28] are suitable to model the internal behaviour of the cell but involve a huge amount of mathematical computations, which makes them practically impossible to be used for smart grid simulations. The integration of an equivalent circuit model (ECM) has been presented for electrical vehicle propulsion in [29], considering SoC as the only impactful parameter. The ECM presented in [30] shows the battery characteristics of an electric vehicle with respect to aging under the World Motorcycle Test Cycle for electric vehicle battery characterization, tracking the internal resistance with one resistive–capacitive (RC) branch. The battery cell model, whose parameters are concerned with physical phenomena such as the effects of SoC and temperature, is explored in [31]. Most of the ECM models of BESSs reported for power system simulations lack one or several affecting parameters related to the performance of Li-ion batteries.

Battery design, sizing, the optimisation of control, and dispatch strategies are more likely to succeed when they are based on more accurate BESS models. Also, there is an urgent need for accurate battery performance models because modern battery management systems rely on such models to track the key parameters of each cell and the whole battery energy storage system. In this paper, a detailed ECM of Li-ion BESSs is presented, and secondly, the developed model is used to accurately size a BESS for different locations and substations in the Åland Islands as a case study to avoid network congestion and defer capital investments in terms of upgrading the network size.

2.2. Modelling Lithium-Ion BESS

Their ability to react quickly, as well as their higher energy and power density, longer cycle and shelf life, low rate of self-discharge, high round trip efficiency and improved safety performance, have meant that Li-ion BESSs have been favoured for stationary grid applications. Li-ion BESSs are capable of acting as flexible energy sources and provide multiple technical ancillary services such as load levelling, peak shaving, islanding/microgrid operation, black start support, network loss minimization, frequency support, and voltage regulation.

Li-ion batteries are intercalation-based energy storage systems which operate as a closed system [32] with very few measurable state variables, making it difficult to properly monitor the states of the battery and maintain safe operation. Voltage, current and temperature measurements are typically used to determine or estimate all other parameters of the battery—typically its SoC and state-of-health. Therefore, it is necessary to understand and precisely model the behaviour of the BESS under various operating conditions.

The Thevenin-based second-order equivalent circuit (SOEC) model is a versatile technique, as it successfully emulates model parameters such as the multi-variable SoC, charge-rate (C-rate), temperature, hysteresis effects, self-discharge and battery aging. SOEC is considered as the benchmark model for Li-ion batteries, as it depicts the charge transfer, diffusion and solid electrolyte interface reactions in the form of resistors and capacitors. The SOEC battery model presented in [33] is based on time domain measurements from hybrid pulse power characterization tests, whose performances are affected by the SoC, operating temperature, C-rate and aging of BESSs. Therefore, the developed SOEC model presents a perfect balance between the accuracy and complexity of battery modelling. Figure 2 shows the proposed dynamic equivalent circuit model for a nickel–cobalt–manganese-oxide (NMC) type Li-ion battery cell. The Open Circuit Voltage (OCV) is modelled as an ideal voltage source, and the internal resistance is modelled as R_i. Two RC combinations are suggested for modelling the Li-ion battery cell, meaning that the dynamic behaviour is modelled as R_1, C_1, R_2 and C_2. The hysteresis effect and polarization effect in the Li-ion cells can be simulated accurately enough with the two RC combinations, and the model structure is simpler compared to more RC combinations. As the actual behaviour of the NMC battery cells is significantly non-linear, all the parameters vary with the SoC, temperature, age and history (number and depth of cycle) of the cell. OCV, R_i, R_1, C_1, R_2, and C_2 are the parameters obtained from the experimental characterization of the lithium-ion battery cell at various SoCs (100% to 0% with a step of 10%), temperatures (15 °C, 25 °C, and 45 °C), C-rates (1C, 2C and 3C) and cycle ages (0, 100, 500, 1000, 1500, and end of life). V refers to the battery cell terminal voltage.

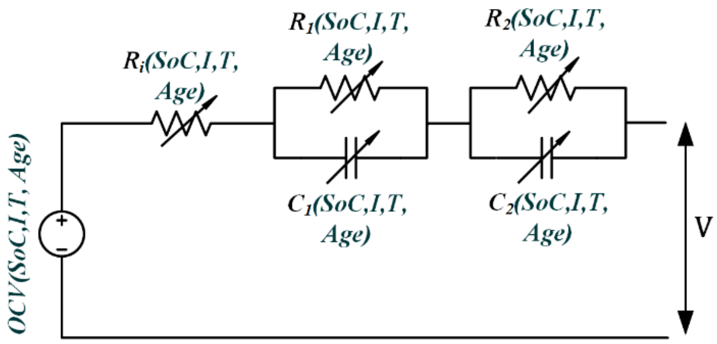


Figure 2. Second-order equivalent circuit (SOEC) battery cell model.

Figure 3 provides a comparison between the simulated and experimental discharge voltages at different aging levels of the NMC battery cell, at a 25 °C and 3C discharge rate, that were recorded as a result of accelerated aging tests. The mathematical representation of the output voltage characteristics for the second-order ECM is given in [33], and the SoC is estimated by the coulomb counting method [34].

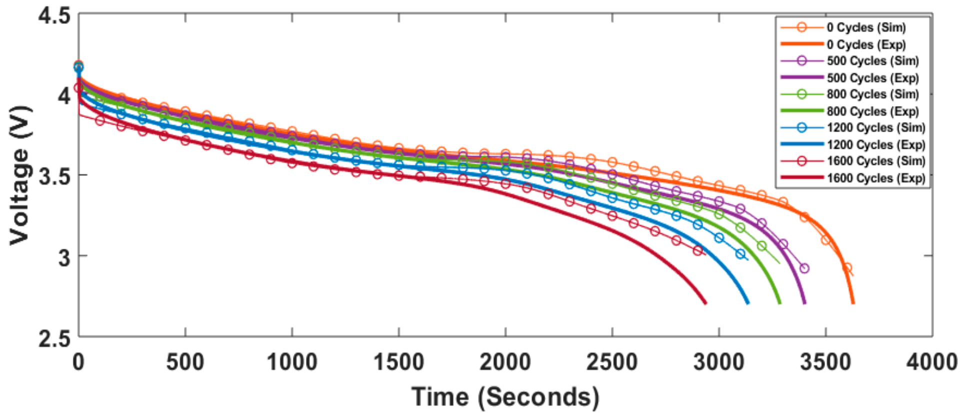


Figure 3. Comparison between simulated and experimental cell discharge voltages with different aging intervals.

The mean relative error was less than 2% for the majority of the discharge cycles, but in some cases (especially at higher aging), the error was greater than 5% towards the end of discharge. It is evident that the overall discharge capacity reduces with aging, which in turn reduces the overall discharge time. The performance of Li-ion BESS changes drastically with aging; thus, the overall discharge energy from the batteries reduces with aging. Predicting the accurate state of energy (SoE) of batteries will aid in the improved design of battery management systems (BMSs) and their respective energy management systems (EMSs). In this study, batteries were considered at their beginning of life to derive the battery size for harbour area smart grids. Hence, modelling the aging characteristics of batteries is a critical task for smart grid applications, because the energy/power status of the BESS is required in order to consider its capability for supplying active power (*P*) and to provide ancillary services such as frequency support or peak shaving.

2.3. Lithium-Ion BESS Grid Integration

A typical topology for the integration of BESS in utility grid applications is presented in Figure 4, which is deployed as a reference for the battery sizing algorithm presented in the next subsection. The nominal BESS voltage ($V_{DC,BESS}$) is considered as 600 V, which is connected to the DC bus. The DC/AC converter connected with the DC bus converts 600 V_{DC} power to three-phase, 400 V_{RMS} AC power. In the Åland Island case, the voltage will be boosted to a 10 kV level by means of a three-phase transformer. The allocation of BESSs in the substation is designed from the voltage, current and power flow data obtained from PSCAD EMT simulations. Results from the simulation provides data input on loading information of each power transmission line and the status (i.e., voltage levels and current flows) at every operational substation.

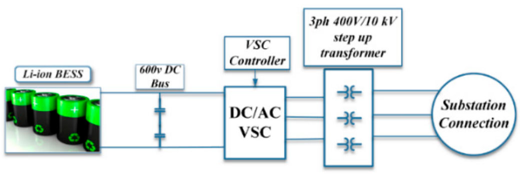


Figure 4. BESS grid integration topology.

2.4. Battery Sizing and Allocation Algorithm

Figure 5 provides a methodology of Li-ion BESS sizing for weak networks/harbours in order to integrate more electric ferry/ship charging stations and RESs. The proposed methodology has been employed in the Åland Islands to reduce or eliminate network congestion and capital investment to upgrade the existing power transmission lines by installing BESSs at critical locations. The line current data obtained from the base case studies of PSCAD simulations are the primary input for this algorithm.

The line current ($I_{,LINE}$) along with the maximum line current capacity (I_{Max}) for each transmission line of 45 kV are provided as input to the algorithm. If $I_{LINE} < I_{Max}$ for a certain transmission line, then the power transmission line is not under congestion.

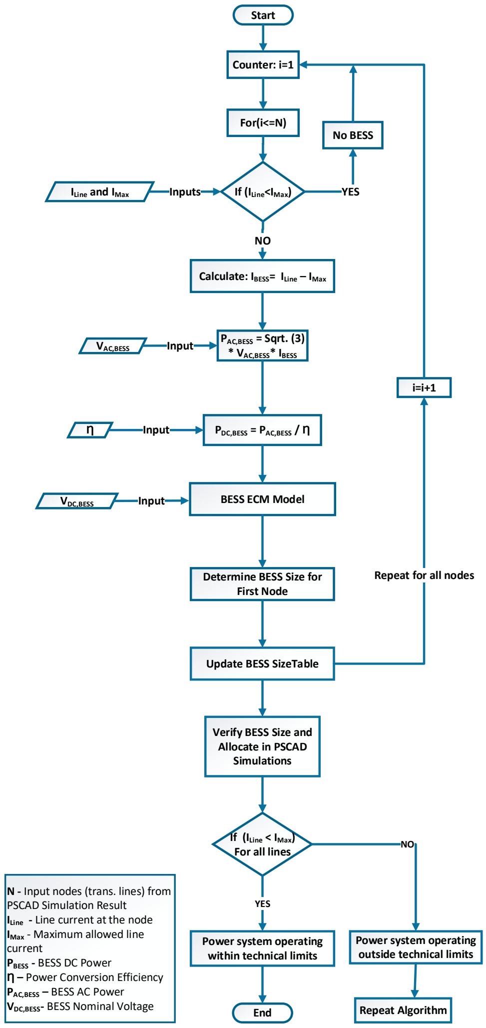


Figure 5. Battery sizing and allocation algorithm. ECM: equivalent circuit model. PSCAD: Power Systems Computer-Aided Design.

However, if $I_{LINE} > I_{Max}$, then that transmission line is under congestion, and there is a need for the installation of BESS in the adjoining substation. Further, the relevant sizing of the Li-BESS for grid applications is imperative considering its economic and environmental burden for a project. The battery cell ECM model aids in the accurate sizing of BESSs for power grid applications. In the later part of the algorithm, The BESS AC voltage ($V_{AC,BESS}$) is given as an input to calculate the BESS AC power ($P_{AC,BESS}$). In the next step, DC power requirements from BESS ($P_{DC,BESS}$) are computed by providing the converter power conversion efficiency, η (95%)as an input. Further, the required BESS nominal voltage ($V_{DC,BESS}$) and $P_{DC,BESS}$ are given as inputs to the developed ECM model. Based on the project requirements, performance-affecting parameters such as the temperature, SoC, age, and current ratings are introduced in the battery model. Based on $V_{DC,BESS}$ and $P_{DC,BESS}$, the battery size at a particular substation is calculated. The parameters of the battery size include the number of series cell connections (N_s) to attain the required nominal voltage levels and the number of parallel string connections (N_p) to obtain required current-carrying capacity, peak discharge power and energy, nominal discharge power and energy characteristics, and nominal charging power requirements. The algorithm then continues on to the next input I_{LINE} until all the inputs are completed. By this method, the optimum Li-ion BESS size at the required substation is determined precisely. Further, the designed BESS is allocated to the selected substations in the PSCAD model of the Åland Islands to perform EMT simulations and record I_{LINE}. In a case in which the transmission lines are still being overloaded (i.e., $I_{LINE} > I_{Max}$), the algorithm in Figure 5 will be reiterated until the right BESS size is obtained.

3. Numerical Studies

This section introduces a real-world test case of a harbour grid in the Åland Islands, which has been simulated by considering future targets of integrating more electric ferry/ship charging stations and RESs with the utilization of BESSs for the years 2022 and 2030. The simulation results and a discussion of the findings are also given in this section.

3.1. Real World Test Case

The geographical location of the grid structure of the Åland Islands, located in the Baltic Sea in Finland, is shown in Figure 6, and a simplified single line diagram is shown in Figure 7. There are two power transmission lines of 110 kV supplied from Senneby (Sweden) and Nådendal (Finland). In addition to the 110 kV transmission lines, two other power transmission lines of 45 kV are supplied from Båtskär (wind park) and Gustavs (Finland). Senneby is an HVAC (high voltage alternating current) transmission line, which is the main power supply for the whole network, whereas Nädendal is an HVDC (high voltage direct current) transmission line, which is used as a backup power supply for the network. Bätskär and Gustavs have weak grid connections because of the intermittent nature of the power supplied from wind power generation. The Föglö substation is currently not operational, but keeping in mind the future marine load demand and integration of renewables, it will be installed between Svinö and Sottunga substations. Moreover, each 45 kV substation is also connected to a 10 kV substation with step down transformer(s) of 45/10 kV to supply marine and other harbour loads. The Åland Islands grid is a quite small and weak power system with many potential medium-size/small harbour areas for future ferry/ship charging stations and the integration of a large amount of RESs. Electric ferries are used for transportation between multiple islands. Typically, the Åland Islands grid is supplied with power from Sweden and Finland. Åland's power system has several substations with different load requirements and the possibility of more than one topology for connecting one substation to another substation. Regarding future load demand, Åland Islands stakeholders are planning to integrate a large amount of renewables (photovoltaic and wind power) in the years 2022 and 2030 with targets to electrify transportation in the main island and between multiple islands. Therefore, significant development in the power system's infrastructure will be needed. This development is considered in two phases for the years 2022 and 2030, which will encounter an increase in the penetration of renewables as well as power demand from electric ferries/ships requiring an onshore power supply and the recharging of on-board batteries at harbours.

To analyse the effectiveness of integrating BESS, the base case and two future case studies for the years 2022 and 2030 have been simulated with the detailed simulation models developed in Power Systems Computer-Aided Design (PSCAD). The base case simulation model considers the maximum loading for the years 2022 and 2030, but without the integration of renewables and BESS, whereas simulation models for the case studies for the years 2022 and 2030 consider the implementation of BESS as well, and they present the effect of the integration of the minimum and maximum number of BESSs on network topologies. The following subsections explain the simulation results obtained from the base case, 2022 case, and 2030 case.

3.2. Simulation Results and Analysis

This section explains the results of base case studies without considering BESSs, and then compares and analyses the results with the integration of BESSs in future case studies for the years 2022 and 2030. For each case study, radial and meshed network topologies have been considered, because the radial topology is the current operational scenario of the Åland Islands power system, and the meshed topology, when compared to the radial, has generally following advantages:

(1) It is more resilient against faults (the electricity supply reliability is better, because customer loads/generated power can be fed from two-directions instead of only one).
(2) The voltage level can be maintained more stably with a meshed topology in different distribution network points (the DG hosting capacity can be typically increased with meshed topology).

However, protection is typically somewhat more complex with meshed than radial networks.

3.2.1. Base Case Studies for 2022 and 2030 without BESS

The base case is simulated to investigate the operation of the Åland Islands electricity network for future predicted marine load demands for onshore power supply and ferry charging stations for the years 2022 and 2030, but without integrating renewables and BESSs. This enables us to examine which transmission lines and other electrical equipment, such as transformers and protective devices, are overloaded. Since the focus of the paper is to design a BESS of a proper size and allocate it at the required substations, only the details regarding the overloading of transmission lines and voltage levels at all the substations of 45 kV are of interest in this paper. The power system in the Åland Islands is operated typically as a radial network, with the following circuits breakers between the substations in open positions: Västanträsk and Storby, Finby and Svinö, Svinö and Föglö, Norrböle and Mariehamn.

The minimum generation and maximum loading cases for 2022 and 2030 are considered in such a way that power supplies from Bätskär and Nådendal are not operational in the simulation model. By considering the above operational criteria along with the predicted load demand for the years 2022 and 2030, the basic single line diagram of the simulation model is shown in Figure 8. Thus, the current operation of power system in the Åland Islands can form two possible islanded sections of the network in radial topologies.

The estimated capacity of power generation from solar photovoltaic sources in 2022 is 33 MW by 3 MW equally at all 10 kV substations, and 30 MW of wind power at Tellholm substation, totalling 63 MW, whereas the estimated capacity of power generation from the integration of renewables in 2030 is 143 MW with reference to year 2022 by installing a photovoltaic source of 10 MW at Hellesby, 118 MW of wind power at Föglö and a 15 MW increase in the power capacity of wind power already installed at Tellholm. A huge amount of power will be generated by RESs, which will replace the grid power supplied from Senneby, Nådendal, and Gustavs substations. The base case simulation shows that it is a challenging task to provide an uninterrupted power supply due to intermittent nature of the power supply from renewables. Therefore, this provides a basis for the installation of a suitable size of BESSs at suitable locations for efficient and stable grid operation. Moreover, the BESSs are supposed to be charged in off-peak time, and especially from the local power generation from renewables, and discharged whenever there is a peak load demand.

The detailed model of the Åland Islands' electricity network is first simulated for the base case in PSCAD without BESSs, and then the line currents along with their maximum current-carrying capacity are fed to an algorithm developed in MATLAB/Simulink, which is used to accurately size the BESS as described in Section 3. Moreover, some techniques are also adopted for controlling the reactive power so that the voltage at different substations remains within the limits, as shown in Figure 9. However, the current flowing for some lines exceeds the upper limits of the current-carrying capacity, as shown in Figure 10. Therefore, BESSs have to be located in those substations to decongest the network and reduce power losses and improve the system stability in the network. The following case studies for the years 2022 and 2030 are carried out in the following subsections, which show that a BESS can reduce the upper limits of the current-carrying capacity of those transmission lines.

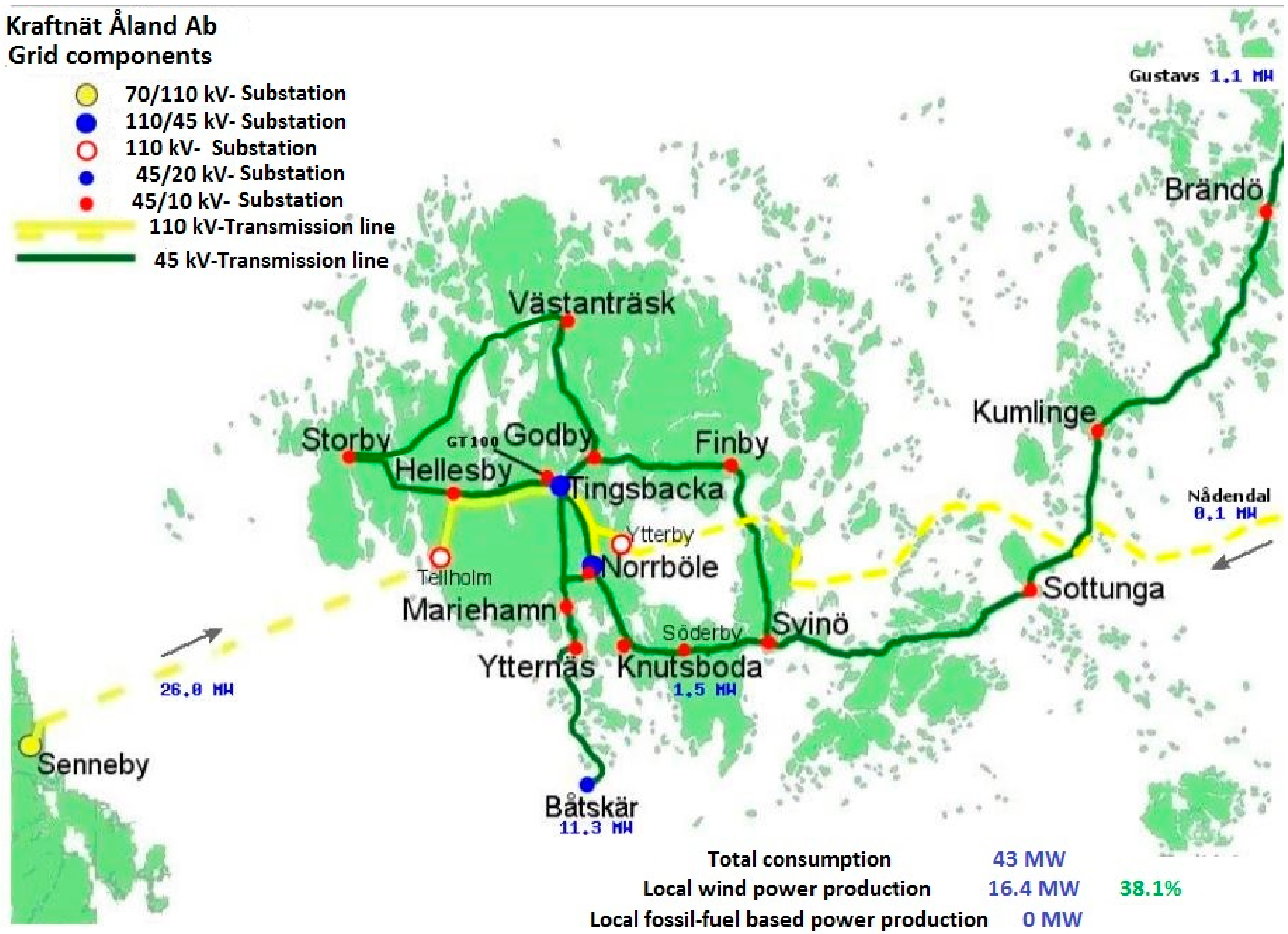


Figure 6. The geographical location and grid structure of the Åland Islands [35].

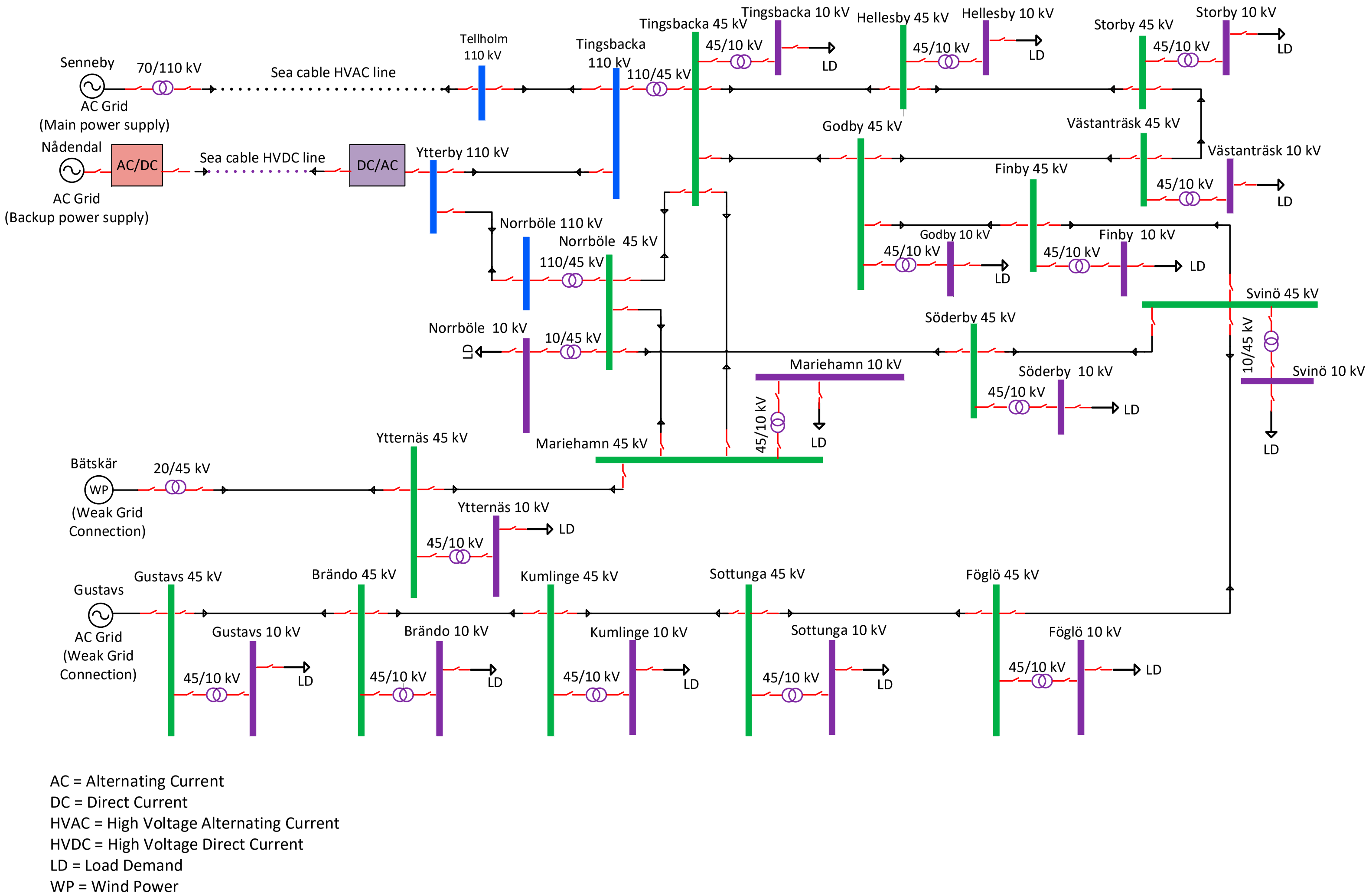
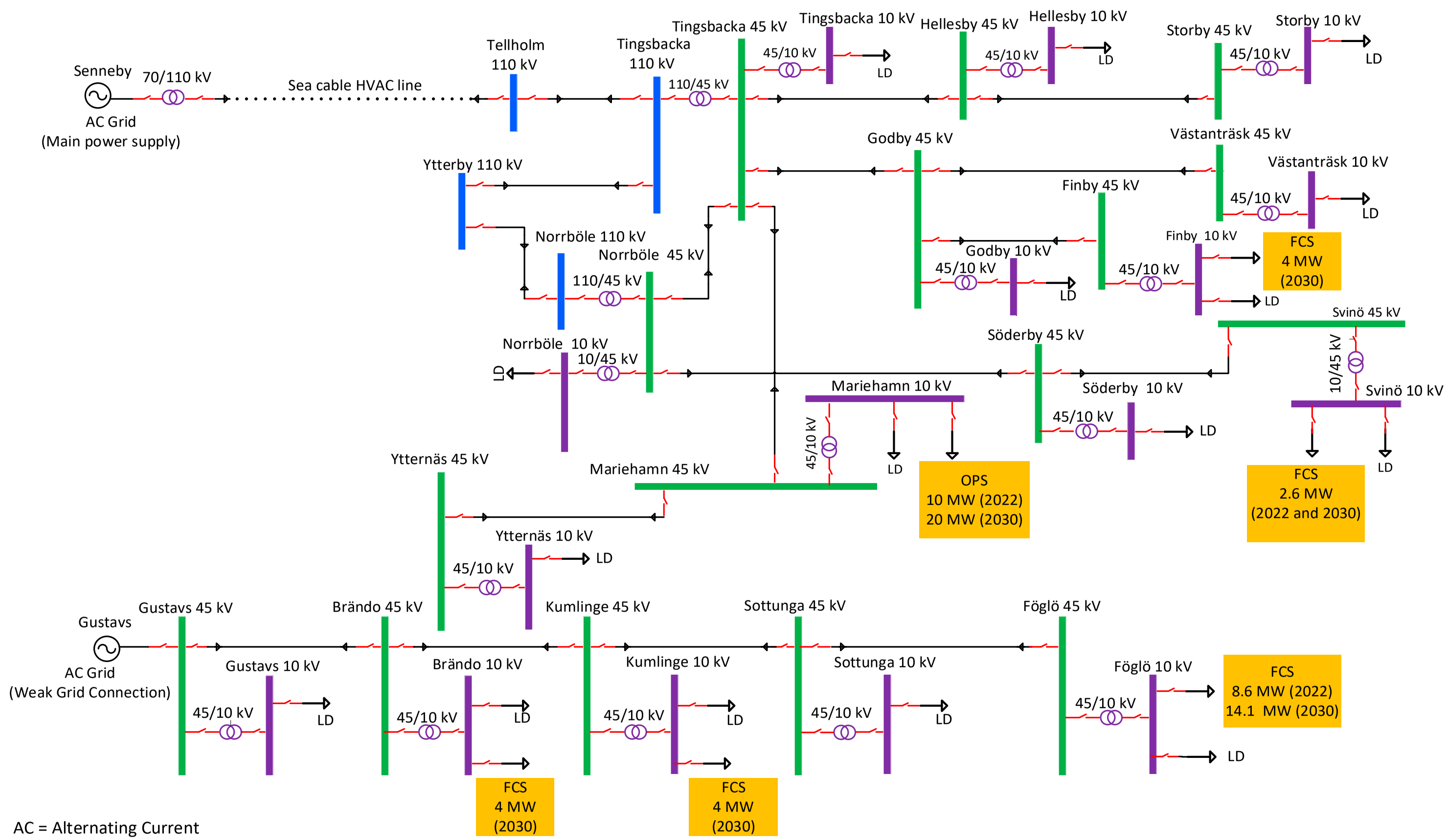


Figure 7. Single line diagram of the Åland Islands' power system.



AC = Alternating Current
FCS = Ferry Charging Station
HVAC = High Voltage Alternating Current
LD = Load Demand
OPS = Onshore Power Supply

Figure 8. Single line diagram of the electricity network in thr Åland Islands for base case studies without BESSs.

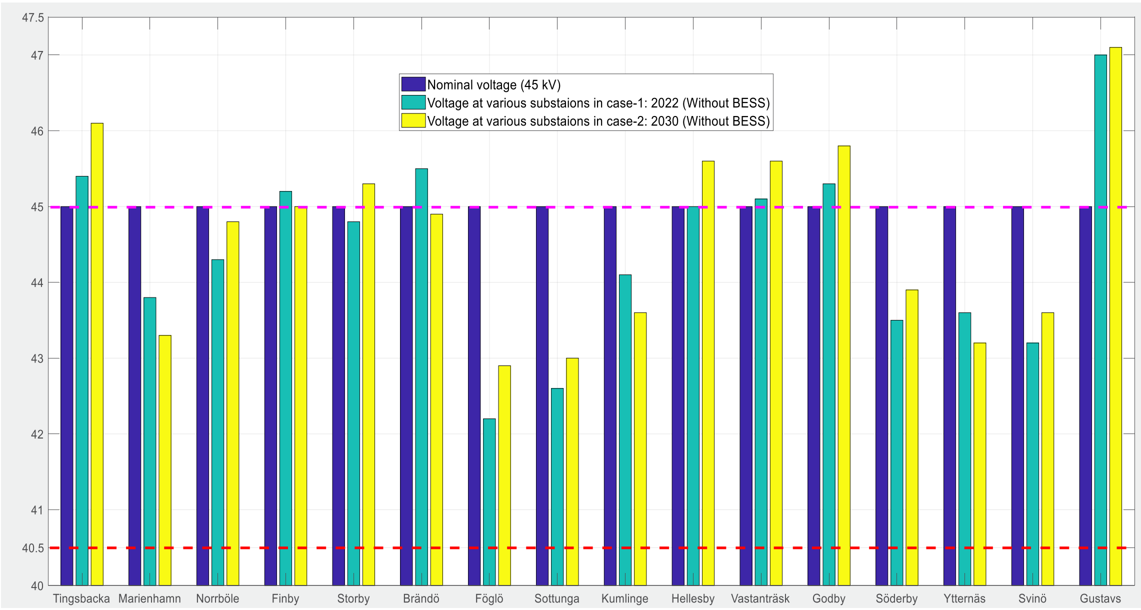


Figure 9. Nominal and operating voltages at the substations in the base case.

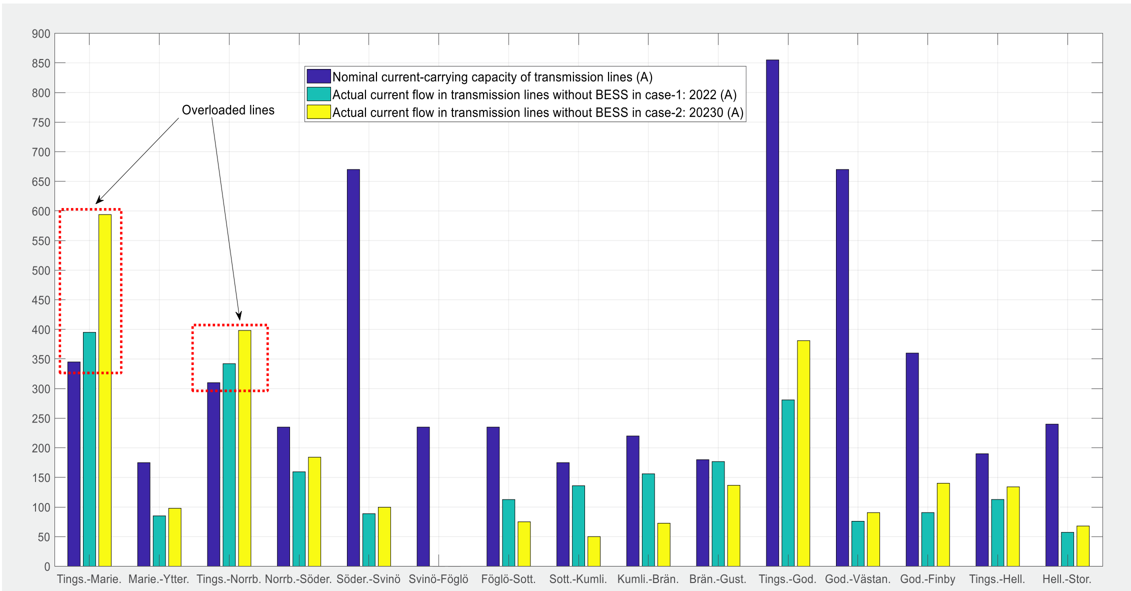


Figure 10. Nominal and actual current flow in transmission lines in the base case study.

3.2.2. Case 1: Year 2022 with BESSs

In the case of 2022, a BESS has been integrated into two network topologies: one is the present operating scenario—i.e., the radial network—and the other is a meshed network by considering the upper islanded network supplied by Senneby. Figure 11 shows the radial network topology with the total predicted increase in load demand of 21.2 MW with reference to the present-day load demand, and this has been distributed at Mariehamn, Svinö, and Föglö substations. In this network topology, the appropriate size of the BESS was found to be of 5 MVA each, and the strategic locations were at Mariehamn, Norrböle and Föglö substations. Figure 12 illustrates the meshed network topology with the same increase in load demand of 21.2 MW, distributed at Mariehamn, Svinö, and Föglö substations. In this network topology, the suitable size of the BESS was found to be 2.5 MVA each, and the strategic locations were at Mariehamn, Norrböle, and Föglö substations. Figure 13 shows the nominal voltage profiles of 45 kV substations' operating voltages without BESSs and with BESSs in radial and meshed network topologies. It has been verified that the voltage profiles have slightly improved with the integration of BESS, and they are within the limits of ±10%.

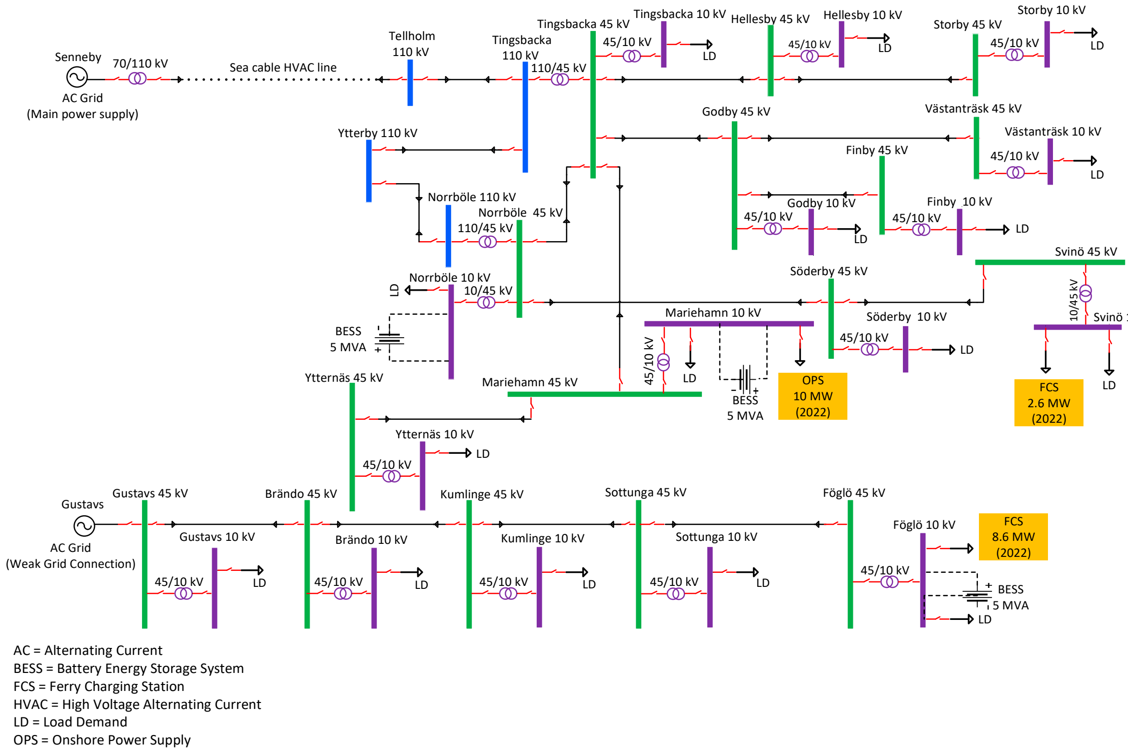


Figure 11. Radial mode operation of the Åland Islands' power system for the year 2022 with BESSs.

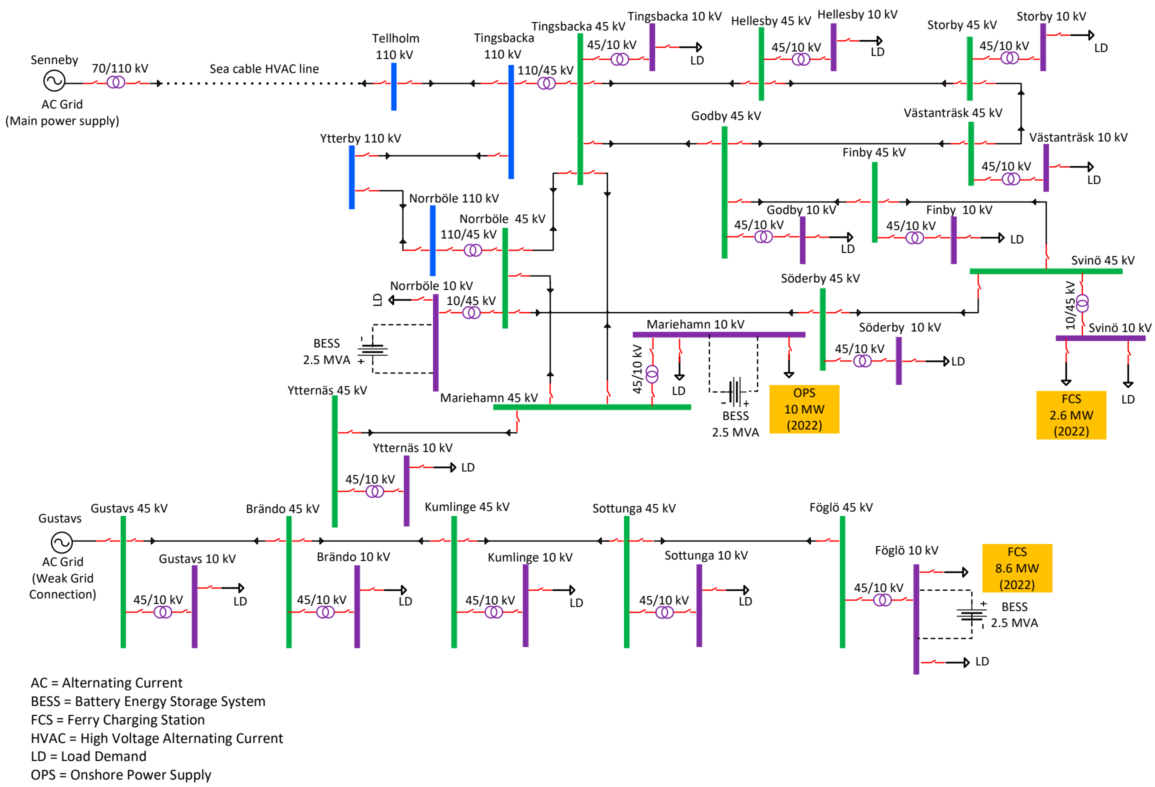


Figure 12. Meshed mode operation of the Åland Islands' power system for the year 2022 with BESSs.

Figure 14 presents the nominal current-carrying capacity of transmission lines and the operational currents of transmission lines without BESSs and with BESSs in radial and meshed network topologies. The simulation results validate that all the transmission lines are now within their nominal current-carrying capacity and none of the power transmission lines are overloaded.

3.2.3. Case 2: Year 2030 with BESSs

In the case of 2030, BESSs have also been located in two network topologies: one is the practical operating scenario—i.e., the radial network—and the other is a meshed network by considering the upper islanded network being supplied. Moreover, two islanded networks supplied from Senneby and Gustavs have also been meshed in order to reduce the size of the BESS. Figure 15 shows the radial network topology with the total predicted increase in load demand of 48.7 MW with reference to the existing load demand, and this has been distributed at Mariehamn, Svinö, Föglö, Finby, Brändo, and Kumlinge substations. In this network topology, the appropriate size and location of the BESS was determined to be as follows: 20 MVA at Mariehamn substation, 7.5 MVA at Norrböle substation, and 5 MVA at Föglö substation. Figure 16 illustrates the meshed network topology with the same increase in load demand of 48.7 MW, distributed at the above-mentioned substations. In this network topology, the suitable size and location of the BESSs was found to be 10 MVA each at Mariehamn and Norrböle substations, and 5 MVA at Föglö substation. Figure 17 shows the nominal voltage profiles of 45 kV substations and operating voltages without BESSs and with BESSs in radial and meshed network topologies. The simulation results show that the voltage profiles have somewhat improved with the integration of BESSs, and they are within the limits of ±10%. Figure 18 presents the nominal current-carrying capacity of transmission lines and the operational currents of transmission lines without BESSs and with BESSs in radial and meshed network topologies. The results verify that all the transmission lines are now within their nominal current-carrying capacity and none of the power transmission lines are overloaded.

3.3. Discussion

The findings of the present study suggest that weak electricity networks with multiple medium-size/small harbour areas require more power and energy capacity to deal with the higher power requirements of modern ships/ferries and other electrical loads at harbours. These higher power requirements of charging stations in harbours can either be accomplished by additional power supplied to harbour grids from the main grids or local power generated from renewables or BESSs. The power system in the Åland Islands has a significant potential for generating electricity locally from renewables and plans to integrate a certain amount of power from wind and photovoltaics sources in 2022 and 2030. This requires huge investments in network capacity enhancements to accommodate the additional power capacity and will cause power fluctuations due to the penetration of renewable energy resources which are intermittent in nature. Therefore, designing a relevant size and location of BESSs is necessary for such a weak network consisting of a massive amount of renewable power generation and electric ferry/ship charging stations. Short-term fluctuations are handled by the present-day Li-ion BESSs, acting as flexible energy sources, and they store energy during off-peak hours, improving the power quality and reliability of the network. This allows the shaving-off of peak loads in the network, consequently reducing voltage drops across the network, and optimising the size and infrastructure cost of passive components such as transformers, transmission lines, etc. This paper investigates the technical advantages of the proper sizing and allocation of BESSs in harbour grids for the Åland Islands' power system. However, an economic analysis of the cost savings of transformers and other equipment owing to the deferral of increasing power capacity against the net battery costs is beyond the scope of the paper.

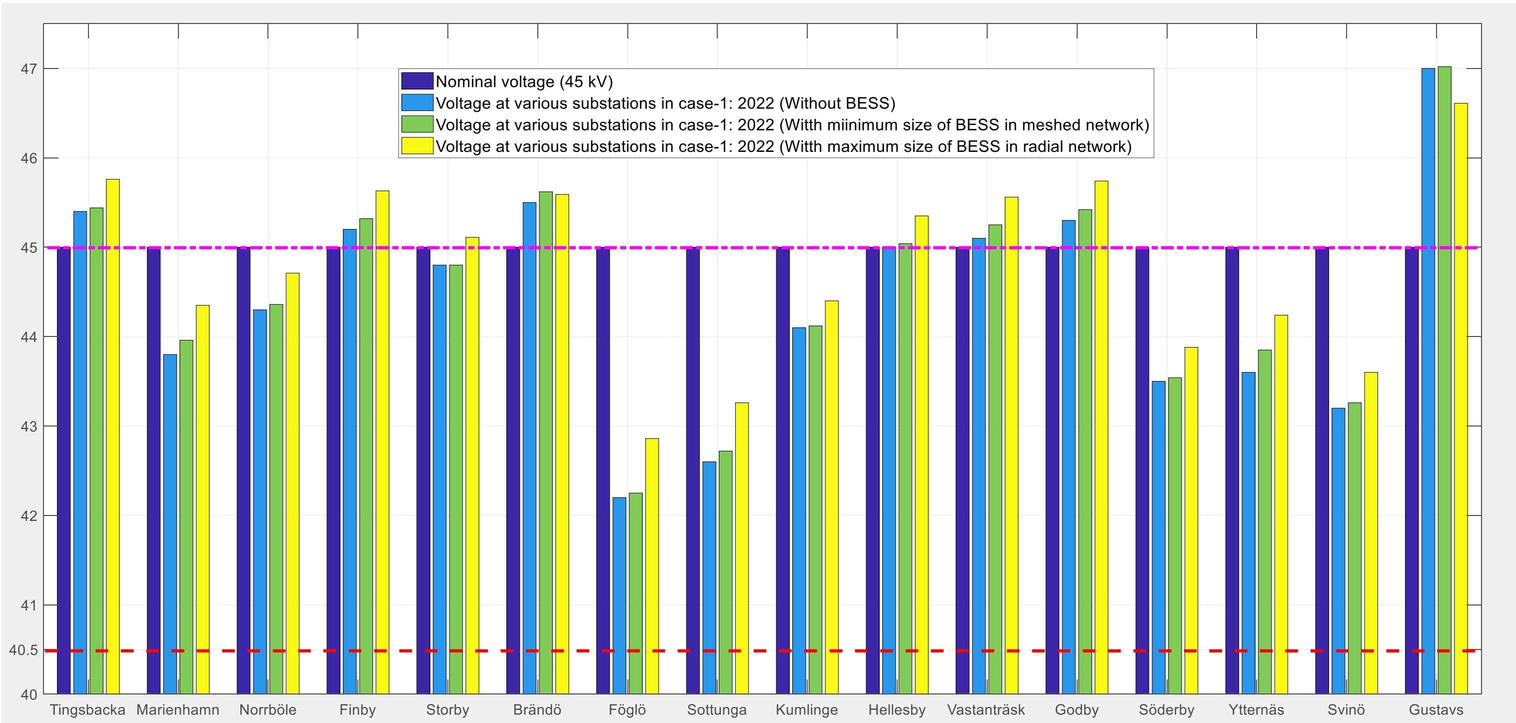


Figure 13. Nominal and operating voltages at the substations for the year 2022 with BESSs.

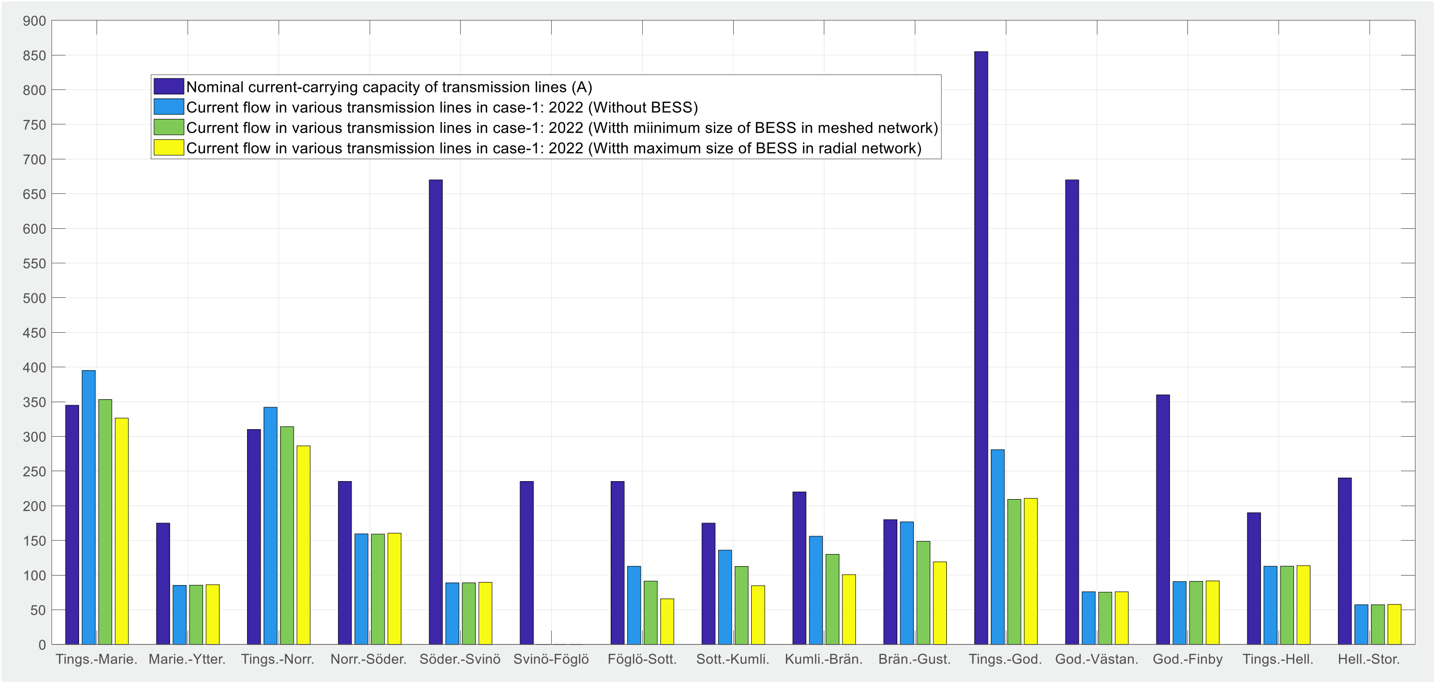


Figure 14. Nominal and actual current flows in transmission lines for the year 2022 with BESSs.

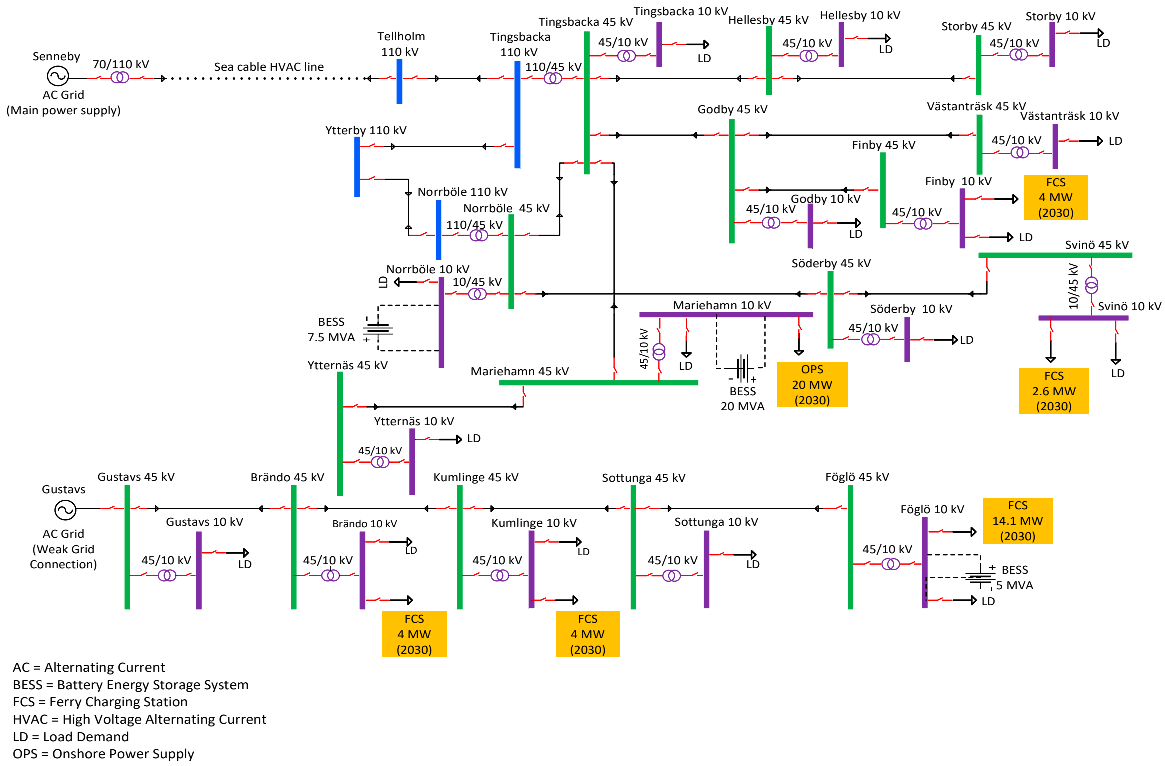


Figure 15. Radial mode operation of the electricity network in the Åland Islands for the year 2030 with BESSs.

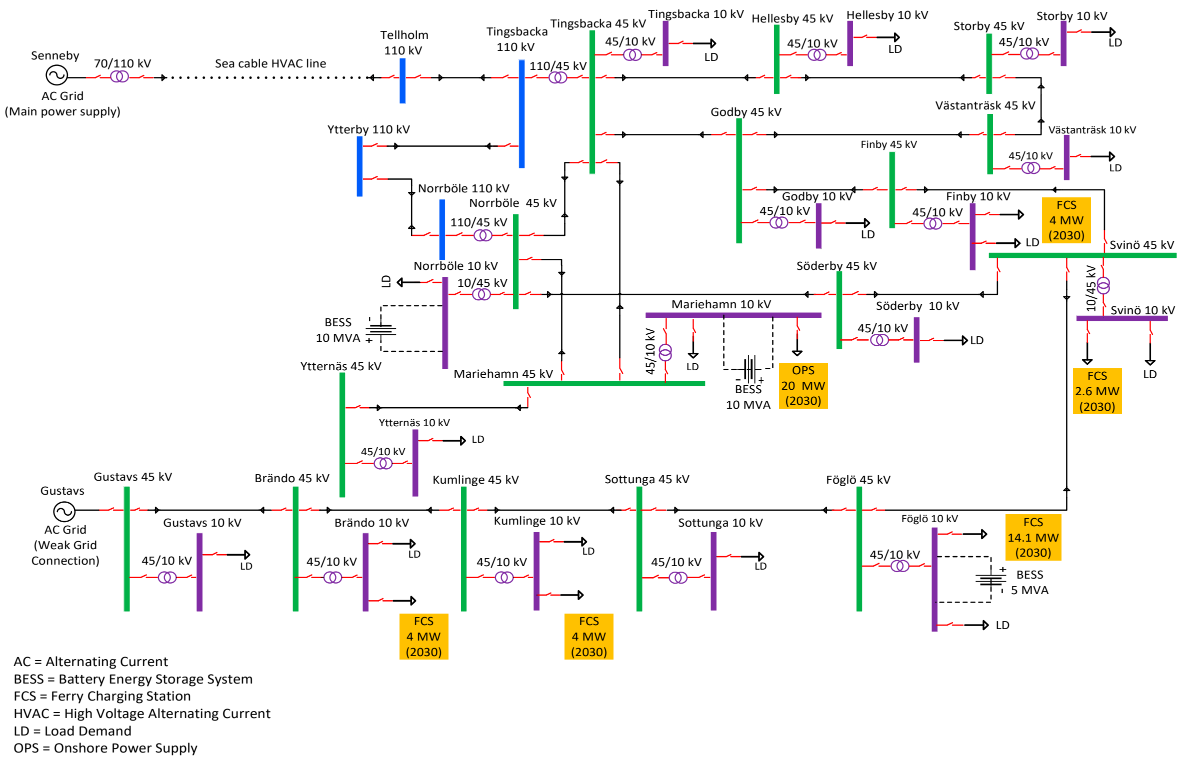


Figure 16. Meshed mode operation of the electricity network in the Åland Islands for the year 2030 with BESSs.

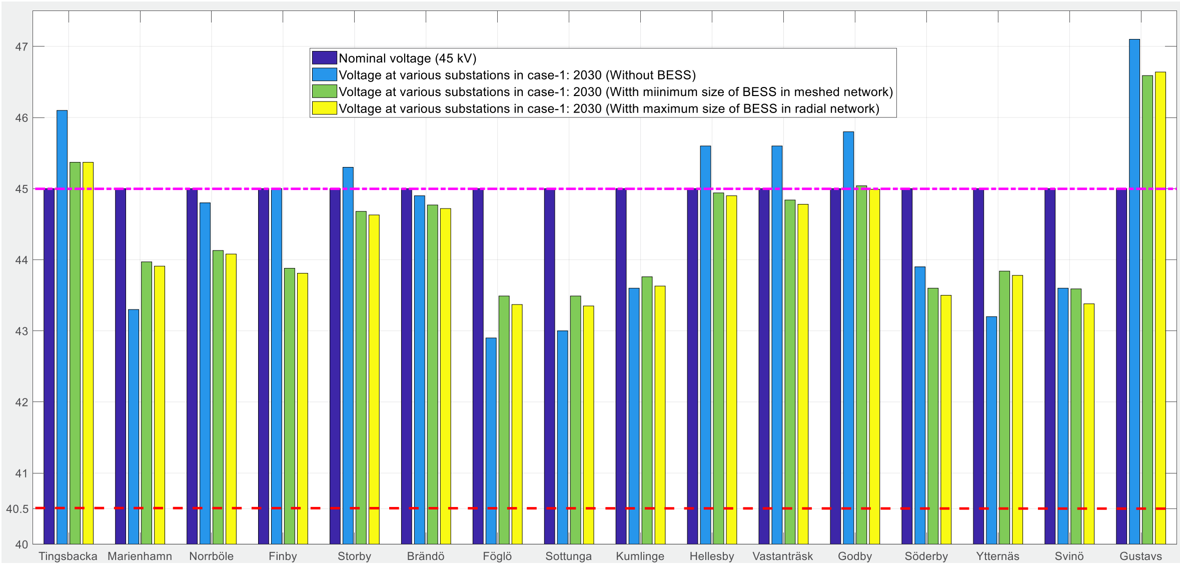


Figure 17. Nominal and operating voltages at the substations for the year 2030 with BESSs.

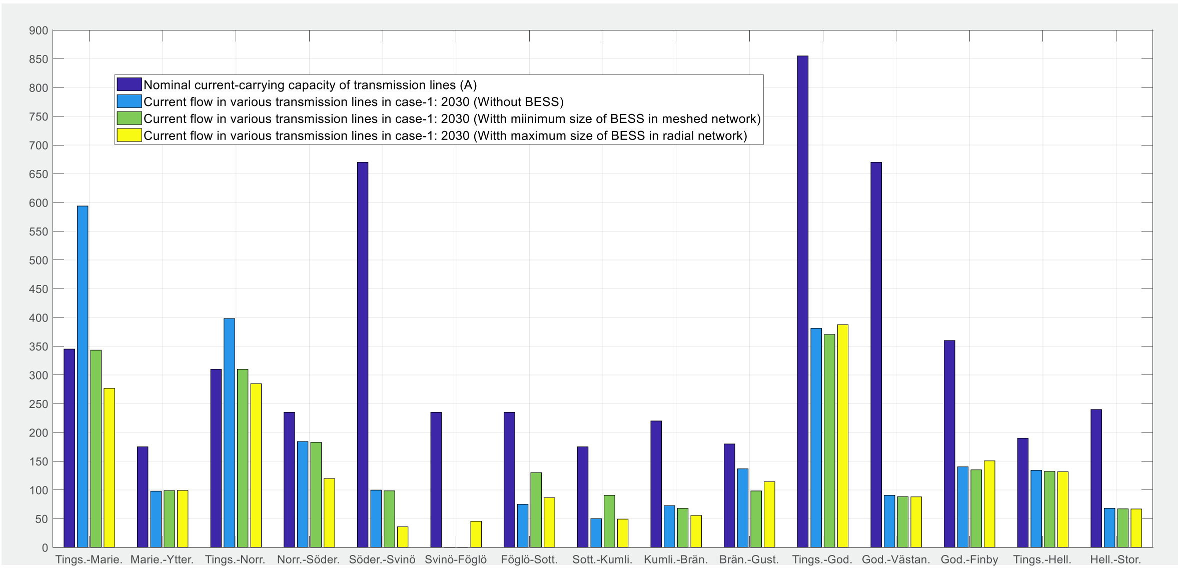


Figure 18. Nominal and actual current flows in transmission lines for the year 2030 with BESSs.

The simulation results of the power system in the Åland Islands illustrate that designing a proper size of BESSs and allocating them at appropriate substations can reduce the overcurrent flowing in certain transmission lines as well as avoid the additional cost of increasing the current-carrying capacity of transmission lines between Tingsbacka–Mariehamn and Tingsbacka–Norrböle. Besides this, Table 2 presents the transformers at various substations which need to be upgraded if BESSs are not installed for the investigated case studies of the years 2022 and 2030. In order to avoid this upgradation of transmission lines, transformers and other grid components, Table 3 summaries the required sizing and appropriate locations of batteries for future case studies of 2022 and 2030. It has been found that the meshed networks, as compared to currently operating radial network, can reduce the size and cost of the BESSs. Besides this, the meshed network can change the operational paradigm by improving the power quality and reliability of the harbour grid in the Åland Islands. However, the meshed networks bring new challenges such as an increase in the complexity of the network and operation of protection relays. The weak power system in the Åland Islands might be threaten power system transient stability issues due to the outage of one of the renewable power plants integrated at one or several locations.

Table 2. Transformer power capacity upgrades at various locations without BESSs.

Substation	Power Capacity of Transformer (MVA)		Upgrade Year
	At Present	Required in Future without BESS	
Västantrask	5	6.3	2022
Söderby	5	6.3	2022
Föglö	–	16	2030
Finby	6.3	10	2030
kumlinge	3	6.3	2030
Brändö	3	5	2030

Table 3. Sizing and Locations of BESS for 2022 and 2030.

Locations	Battery Size Required in 2022 (MVA)		Battery Size Required in 2030 (MVA)	
	Radial Topology	Meshed Topology	Radial Topology	Meshed Topology
Mariehamn	2.5	5	20	10
Nörrbole	2.5	5	7.5	10
Föglö	2.5	5	5	5

4. Conclusions

This paper has focused on the proper sizing and allocation of BESSs for harbours in weak power systems which plan to integrate RESs and electric ferry/ship charging stations into an existing electrical network. Since power from renewable energy resources is volatile, the accurate sizing and installation of the BESSs at proper locations are necessary as they can reduce the peak load demand, avoid the expansion of the existing capacities of transmission lines, and defer capital investment in other electrical equipment. The maximum current-carrying capacity, along with the operational currents in all transmission lines obtained from the simulation of the detailed PSCAD grid model, are fed to the algorithm developed in MATLAB/Simulink to obtain a proper size of BESSs at suitable locations. Moreover, the developed algorithm has been tested by taking existing original field data of the weak power system in the Åland Islands, and the results validate that the size and locations of the BESSs are accurate enough to cope with the maximum load demand considered in the case studies of 2022 and 2030 without overloading any transmission line. Congestions in the network as well as the upgrading of network components (transmission lines, transformers, and protection schemes) for the future scenarios of 2022 and 2030 could be avoided by integrating a suitable size of BESSs at certain locations. The simulation cases with a minimum sizing of batteries can reduce the peak load demand of the network, but the few line currents are near to the maximum allowed capacity limits. However, in practical operating scenarios, the maximum sizing of batteries is required, and the simulation results show that all the line currents are below the operating limits for every line.

The authors are interested in investigating other challenging tasks for future studies, such as power system protection, which is typically more challenging in meshed networks. Besides this, the power system in the Åland Islands might be at risk of transient stability issues due to the variable nature of the new low-inertia renewable power plants integrated at one or several locations. Therefore, in future, the power system stability and the role of BESSs in mitigating issues should be carefully studied. In future studies, the effect of battery sizing and location, while considering accurate profiles of power production from renewable energy sources, will be evaluated. Studies related to batteries at different stages to evaluate the role of battery aging in designing control strategies of BESSs in harbour area smart grids will also be considered for future research.

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Abbreviations

AC	Alternating current
BESS	Battery energy storage system
DC	Direct current
DG	Distributed generation
ECM	Equivalent circuit model
KBM	Kinetic battery model
Li-ion	Lithium-ion
NMC	Nickel–cobalt–manganese-oxide
PSCAD	Power Systems Computer-Aided Design
PV	Photovoltaic
RC	Resistive–capacitive
RES	Renewable energy source
SoC	State of Charge
SOEC	Second-order equivalent circuit
VSC	Voltage source converter

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Smart Control of Battery Energy Storage System in Harbour Area Smart Grid: A Case Study of Vaasa Harbour

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***Abstract*— Battery energy storage system plays an essential role for optimally controlling and managing power of modern harbour grids so as to support electric vessels requiring onshore power supply and battery charging system. Designing an appropriate size of battery energy storage system of any harbour grid require precise data of power consumption as well future planned load. This paper presents a practical approach where a charge/discharge strategy is applied in such a way that peak-load demand of harbour grid is shaved off by discharging the battery during peak demand load and charging it during off-peak load demand. A suitable battery energy storage system along with its control algorithm is designed for Vaasa harbour grid with the obtained real data of annual power consumption and available power resources. Vaasa harbour grid model is developed in MATLAB/Simulink and a control algorithm is developed for the power flow to and from battery energy storage system by charging and discharging through bi-directional dc-dc converter. The results show that battery energy storage system is a suitable solution for harbour grids to cope with growing demand of new electric ships optimally in harbour grid without extensive renovation of the power supply infrastructure.**

Keywords— Battery energy storage system, Harbour grid, Microgrid, Onshore power supply, Power control

I. INTRODUCTION

Seagoing vessels play a crucial role in global trade [1], but mostly they employ cheap quality fossil fuel for power generation from diesel engines onboard. The major issues concerning modernizing these vessels are to reduce environmental pollutions while maneuvering as well as staying at berth [2], saving fuel, and increasing energy efficiency [3]. These problems can be well tackled in harbours with power being supplied from microgrid consisting of renewable energy sources, and battery energy storage system (BESS) in parallel with main grid power supply. In this regard, the concept of harbour area smart grid (HASG) [4][5], has been proposed recently in the literature, which can support onshore power supply as well as charging of batteries for the modern vessels [6].

The process of shutting down auxiliary diesel engines of ships and obtaining an onshore power supply for the ships' auxiliary services during a stay in port is historically termed 'cold-ironing' or 'onshore power supply' or 'shore-to-ship power' [5][7]. The HVSC standard [8] has been developed and unanimously adopted by world leading organisations, namely the IEC, ISO and IEEE, for promoting shore-to-ship power supply. Shore-to-ship power supply is an emerging paradigm [9], and it has been observed that the shore-to-ship power can reduce CO2 emissions significantly at harbours [10]. The European Directives also force the ships to use either low-sulphur fuel for onboard power generation in vessels or onshore power supply while staying at harbours to curb greenhouse gas emissions, air and noise pollutions [11]. The shore-to-ship power should be supplied by a near zero or emission-free power generation sources and smart grids having electric power generation from multiple renewable sources (wind, photovoltaic, etc.) nearby harbours along with utility power supply can provide economical as well as clean energy for onshore power supply [4][12]. Moreover, use of energy storage at harbours can reduce air emissions as well as facilitate the power generation with respect to optimal load scheduling [13][14]. A BESS employed by modern vessels needs to be recharged after reaching a certain depth of discharge. The concept of harbour area smart grid (HASG) [4][5] and seaport microgrids [15] aims to coordinate multiple renewable energy resources along with main grid supply to optimally balance power and energy requirements of hybrid and electric vessels requiring shore-to-ship power supply, battery charging stations, and other necessary loads at harbours.

There are several challenges for the HASG such as balancing of power for the distributed energy resources (DERs) inside the microgrid during grid-connected mode, islanding detection of a microgrid, and smooth transition of microgrid from grid-connected to islanded mode [16]. It is also required to maintain the voltage and frequency for onshore power supply according to the High Voltage Shore Connection (HVSC) standards [8]. Besides these challenges, harbours will require significantly higher amount of power and energy consumption in future especially because of need of onshore power supply, and battery charging stations of modern electric ships. The power consumption and schedule of each vessel arriving at and leaving from harbour is different, therefore power and energy consumption of a harbour can be optimized in such a way that peak-load load demand can be shaved off. Thus, future harbour grids will require suitable objective functions to design harbour grid in such a way that losses are minimized, and the available resources are operated and controlled efficiently and economically. Therefore, it is necessary to design a harbour grid optimally so that electric power and energy can be efficiently utilised while managing electric power supply and consumption according to the needs of harbour operations and availability of renewable energy resources. The various types of battery technologies, such as lead-acid, lithium-ion, and redox-flow have been employed in various harbour grids depending up on specific power and energy requirements load profiles [17].

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The objective of the paper is to develop a control algorithm for battery energy storage system in harbour grids in such a way that power and energy consumption can be economically and efficiently fulfilled with the available energy resources. Essentially the applied approach is suitable to avoid capital cost of installing extra power system infrastructure in harbour grids to meet the peak-load demand. As a case study the real data from Vaasa harbour is applied which is currently being renovated with shore-to-ship power supply available for a new hybrid electric system based ferry Aurora Botnia. The optimization target is achieved by developing a simulation model of Vaasa harbour grid with hourly data of annual power consumption of various loads and suitable optimization techniques is applied to control the charge/discharge characteristics of battery energy storage system. These charge/discharge characteristics are decisive in designing a proper size of battery energy storage system, reducing peak-load demand of a harbour, avoid expansion of transmission line. Thus, harbour grids behaving as a microgrid will have more flexibility to manage power optimally in such a way that exchange of power between ports and ships will also be possible.

The rest of the paper is organised as follows. Section II presents the detailed single line diagram of feeder topology for Vaasa harbour grid connection. Section III provides a methodology of developing a control algorithm for battery energy storage system in Vaasa harbour grid which aims for charging and discharging battery energy storage system based on shaving off the peak-load demand while considering the power constrains. A case study has been considered by employing real grid data of hourly annual power consumption of the secondary substations to control power and energy for Vaasa harbour grid. The simulation results are discussed in Section IV, and the conclusion is presented in Section V.

II. Simulation Model of Vaasa harbour Grid

This section introduces the simulation model of Vaasa harbour grid based on real data obtained from the local distribution system operator Vaasan Sähköverkko and harbour operator Kvarken port of Vaasa. First, the detailed single line diagram of Vaasa harbour grid topology is presented and then based on that the Vaasa harbour grid model is developed using MATLAB Simulink.

A. Vaasa harbour grid topology

The single line diagram in Fig. 1 shows the detailed feeder topology of Vaasa harbour, where the power is being supplied from Vaasa electric supply. The 20 kV medium voltage (MV) main feeder named J08 is supplied from the 110 kV transmission grid through a primary transformer of 110/20 kV. This J08 feeder supplies several secondary substations named as 4697, 630, 666, 59, 55, and 8017. Now, the new secondary substation named 4949 is under construction for enabling the shore to ship power supply to the new hybrid electric ferry. At present only this ferry is considered for shore to ship power supply and maximum power demand is assumed to be 2 MW, while the duration of shore to ship power supply depends on the cruising schedules. In reality there will be four connection points for the ferry in the quay, and interlocking switch is placed in such a way that enables various ways of docking with the integration of battery energy storage system as shown in Fig. 1. This new hybrid electric ferry will travel in the route between Vaasa and Umeå as shown in Fig.2 (Geographical map).

B. Simulation model in MATLAB Simulink

The single line diagram in Fig. 1 has been modelled in MATLAB Simulink as shown in Fig. 3. The real data obtained for each component such as for transformers, conductors (cables), hourly load profile of each secondary substation has been employed in the model. The new connection at 4949 secondary substation for Vaasa harbour grid will provide shore to ship power supply to the new ferry which will have a fixed schedule of arriving and leaving the seaports. Therefore, keeping in view the schedule of new ferry, load profile for onshore power supply at that node (4949) has also been calculated and its data has been employed in the MATLAB Simulink model. It has been observed that there is certain time, where the peak-load demand is high and may not be supplied with the current carrying power capacity of the MV feeder and power transformers. Therefore to shave the peak-load demand, a suitable size of battery is designed in such a way that it charges during off-peak load demand and discharge during peak-load demand. The bi-directional AC/DC converter is connected in between AC bus of 0.69 kV and battery energy storage system, which is used to charge/discharge the battery depending upon power requirements. Thus, the proposed methodology of controlling the battery energy storage is based on real data of harbour grid and the schedule of shore to ship power supply and it aims to keep the power obtained from the grid within the capacity limits by charging and discharging the battery.

III. The Proposed Methodology

Vaasa harbour grid plans onshore power supply for new ferry and the schedule of the vessels staying at seaports determine the peak-load demand of harbour grids. This paper aims to develop control algorithm for charge/discharge cycle of the battery energy storage system for Vaasa harbour grid to cope with peak-load demand economically. Moreover, power and energy management of the harbour grids can be well tackled by avoiding extra burden on the existing power infrastructure such as: power cables and, power transformers. First of all, the developed model is simulated in MATLAB Simulink without designing the battery energy storage system for it. Then it has been observed that the peak-load demand of the harbour is higher than the existing rating of electrical infrastructure, such as rating of the transformers and cables. The mismatch of maximum load demand and normal ratings of the equipment are decisive factor for designing an appropriate size of the battery energy storage system. Afterwards, the daily, weekly, monthly and yearly energy demand of Vaasa harbour grid is calculated for determining charge/discharge cycle of the battery. As the energy demand is different at different time depending upon schedule of shore to ship power, which varies at different days and season of the year. Therefore, energy demand is decisive in charge/discharge cycle of the battery energy storage system. The size of BESS and charge/discharge cycle are considered in such a way that the renovating of MV feeder is avoided and the peak-load demand is met without violating HVSC standard requirement of voltage limits.

The following equations are used to calculate the size of the battery energy storage system:

$$P_{grid}+P_{battery}= P_{demand} \quad (1)$$

$$P_{demand} = P_{harbour}+P_{S2S} \quad (2)$$

$$\text{Constraint: } P_{grid} \leq 2.5 \text{ MW} \quad (3)$$

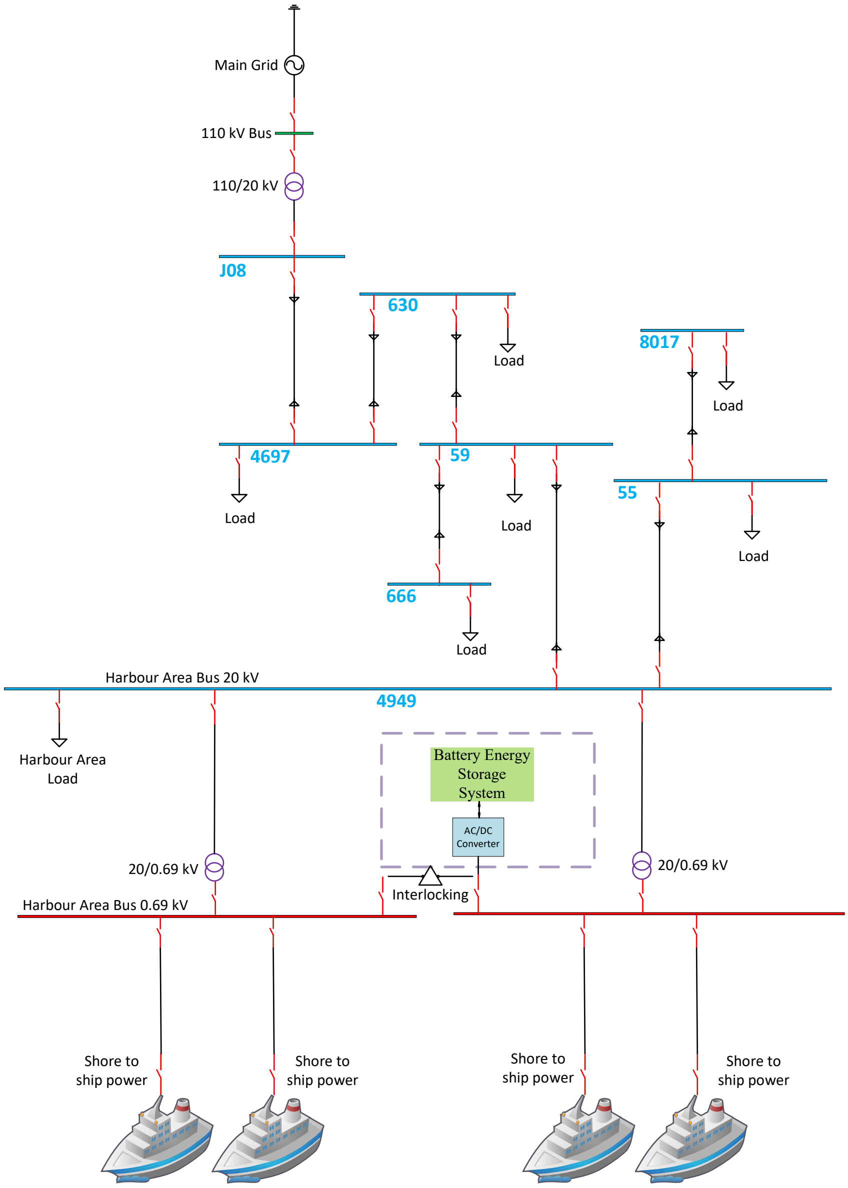

Fig. 1. Feeder topology of Vaasa harbour

Where P_{grid} is power from the grid, $P_{battery}$ is power supplied by the battery, P_{demand} is total power demand at harbour, $P_{harbour}$ is harbour load, and P_{S2S} is shore to ship power. The energy storage capacity for the battery energy storage has been designed with the following constrains:

$$20\% \leq SOC \geq 100\% \qquad (4)$$

$$SOC \leq 0.2C \qquad (5)$$

The following flow chart in Fig. 4 shows the control algorithm for an energy management system of the proposed methodology. It shows that battery is charged between 20-100% whenever the power demand is less than grid power and it is discharged whenever power demand is higher than grid power and battery has state of charge (SOC) between 20-100%. In all, other cases battery is in idle mode of

Fig. 2. Ferry route of Vaasa-Umeå

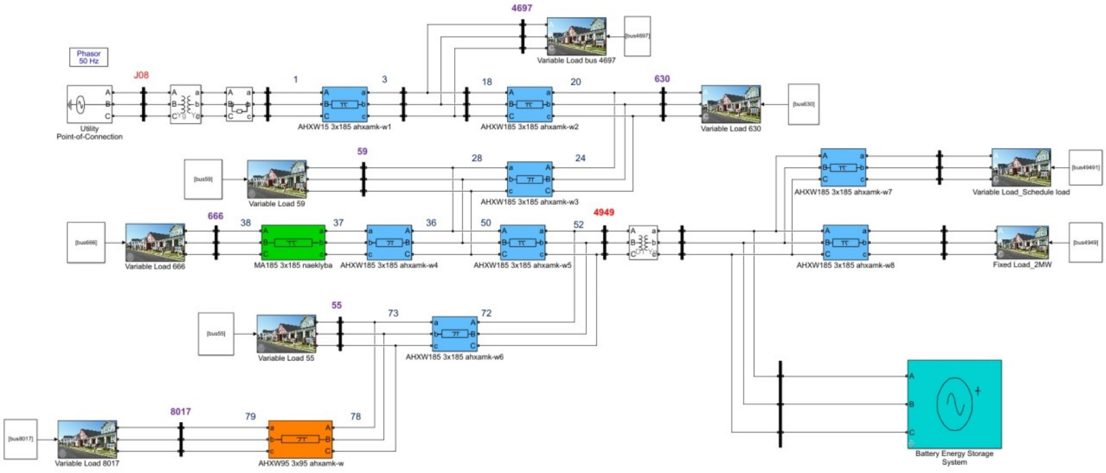

Fig. 3. Simplified MATLAB Simulink Model of the proposed power system

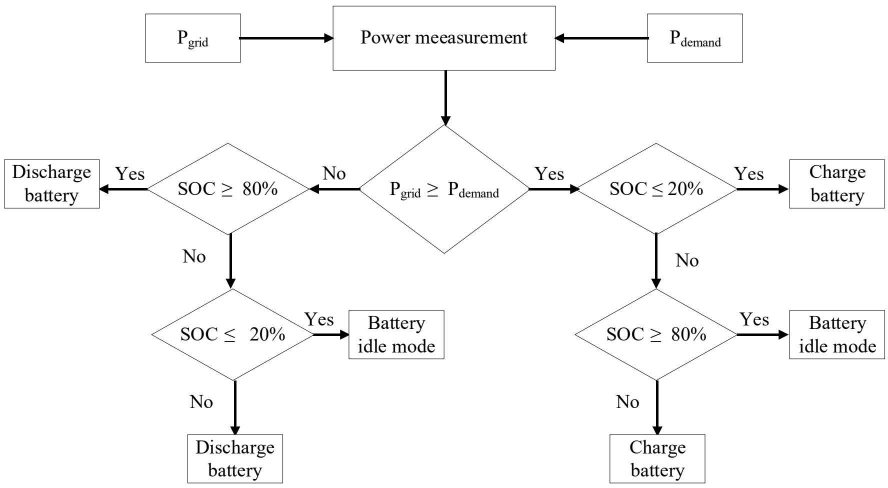

Fig. 4. Control algorithm of energy management system

operation because it is recommended to not to discharge lithium ion battery over 80% depth of discharge. The sizing of battery energy storage has been designed in such a way that battery is charged or discharged throughout the operation and idle mode of operation is avoided especially when power demand is higher than power being supplied by the grid.

IV. Results

The simulation results are shown in Fig. 5, Fig. 6, and Fig. 7. They are obtained by integrating proper size of battery energy storage system into Vaasa harbour grid and implementing charging and discharging the battery according to the developed algorithm.

The Fig. 5 shows the grid power, load power and battery power. The maximum load demand of Vaasa harbour grid is 4 MW at certain times of the year depending upon schedule of onshore power supply, whereas the harbour grid has the limited power capacity of 2.5 MW from the grid. Therefore, the extra power is being supplied by the battery in such a way that peak-load demand of harbour grid is shaved off. It represents that whenever the load demand is higher than the grid power, then the battery power is being supplied by discharging the battery. Whenever, the power demand of the load is less than the grid power, then the battery is being charged. Thus, the applied control algorithm performs well and the net power, which is difference of grid power and demand power is utilised in terms of charge/discharge cycle of battery depending upon power requirement of harbour grid.

The Fig. 6 shows the graph of state of charge (SOC) and power being charged or discharged by the battery. It shows that whenever battery is being charged, the SOC increases, and the power is being absorbed by the battery as shown negative power in the graph. On other hand, whenever the battery is being discharged, the SOC decreases, and power is being supplied by the battery as shown positive

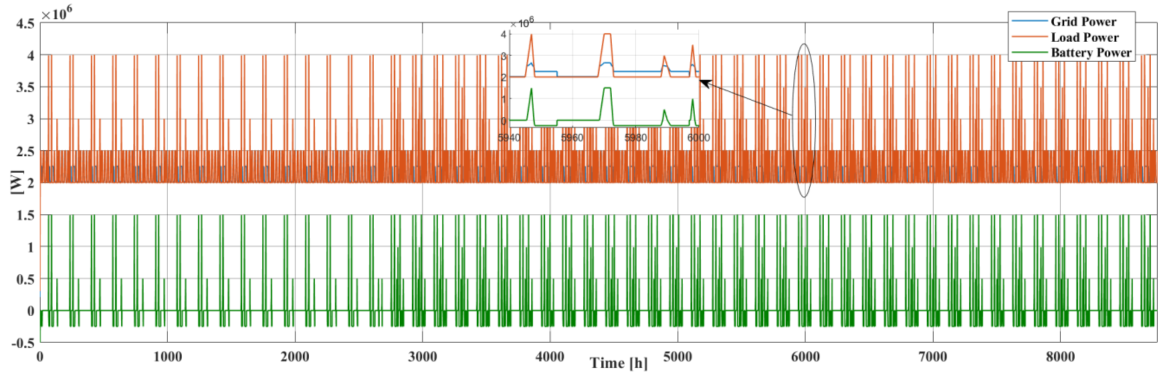

Fig.5. Grid power, load power and battery power

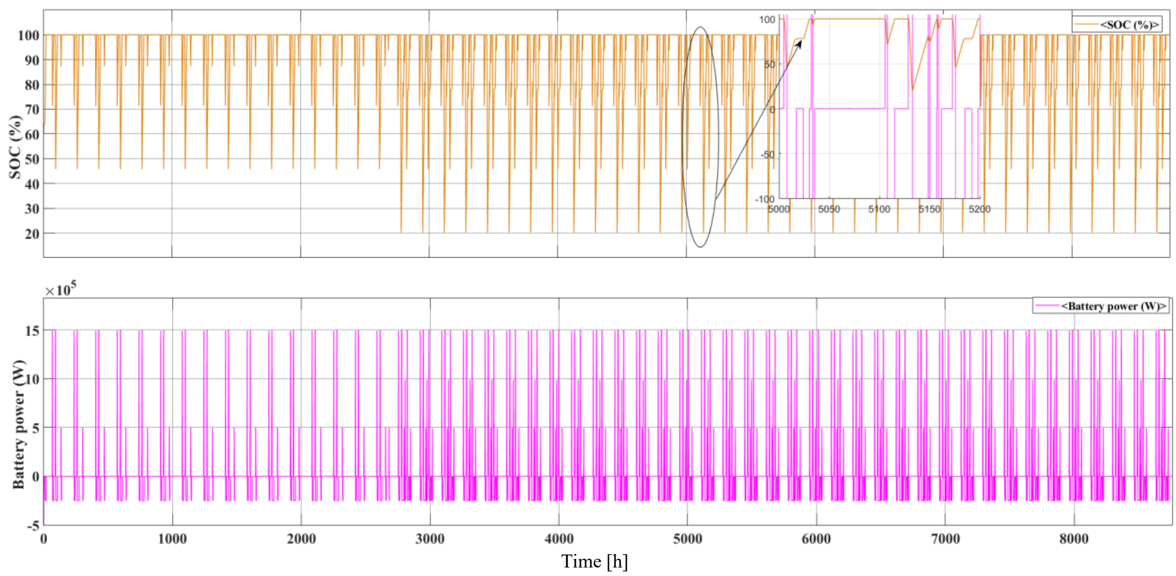

Fig. 6. State of charge and charge/discharge of battery

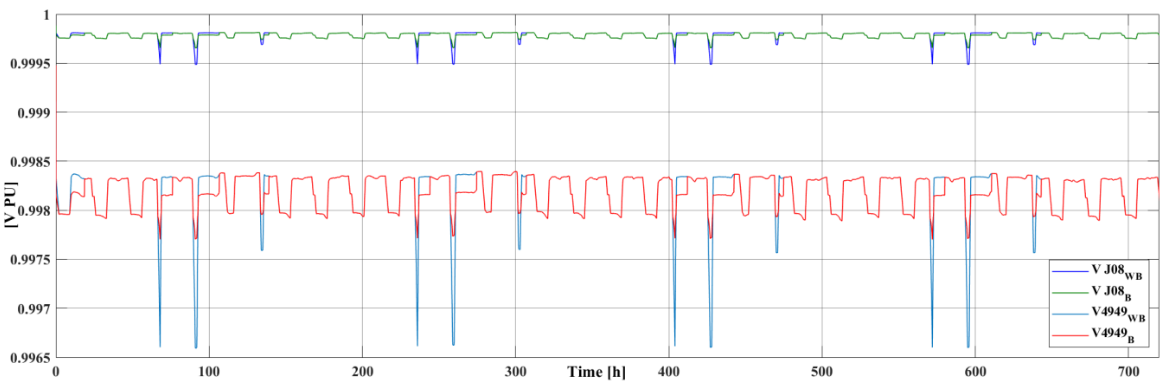

Fig. 7. Voltage profile at secondary substations without and with battery

power in the graph. The battery is in idle mode of operation, when SOC=100% and load demand is also less than the power being supplied by the grid. It is also due to the fact that the main objective of this research paper is to shave peak-load demand and therefore this limits to further reduce the size of battery energy storage system because of variable nature of load profile. The battery energy storage system is designed in such a way that it has also constant charging current so that the idle time can be minimized as much as possible.

The voltages at secondary substations are also within limits as described by the HVSC standards. It has been observed that voltages at all the secondary substations are within the specified limits at all over the year. Moreover with the integration of battery energy storage system, voltage profiles at all the buses have been further improved. The results of voltage profile of two main buses (J08 and 4949) in per unit have been shown in Fig. 7 for the sample time of one month.

The results are obtained by doing multiple simulations in order to keep the idle time and size of the battery as minimum as possible to cope with peak-load power demand of harbour. However, the major concern was the schedule of the ferries requiring suddenly high amount of power in short interval of time. Due to this, the idle time and size of the battery energy storage system can not be further reduced.

V. Conclusion and future work

This paper illustrated how the power and energy demand of the harbour grid may vary at different time of the day, different season of the year and so on. It mainly depends upon the schedule of shore to ship power supply of the new hybrid electric ferry. It might be challenging to cope with the high power demand during peak-load of modern harbour grids with the available electrical infrastructure. Therefore, battery energy storage can play a significant role for stable and reliable operation of the harbour grid. It has been concluded through a case study of Vaasa harbour grid that capital cost on electrical equipment such as transformers, cables etc. can be avoided by employing an appropriate size of battery energy storage system and power demand can be controlled by charge/discharge cycle of battery energy storage system. Thus, modern harbour grids in future can employ the proposed methodology and control power and energy requirement with the predetermined load profile data.

In future, the developed model can be utilised when considering the integration of renewables and battery charging system to the Vaasa harbour grid. Then the smart control and optimisation techniques can be further developed to minimise the operational cost of power consumption. The optimal design of the battery storage device can be determined with by employing some suitable decision-making model. This could be achieved by integrating forecasting methods to anticipate peak load periods. The trade-off between the size of the battery and the profitability of the investment can also be compared to the load peaks frequency.

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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, the SCL file 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

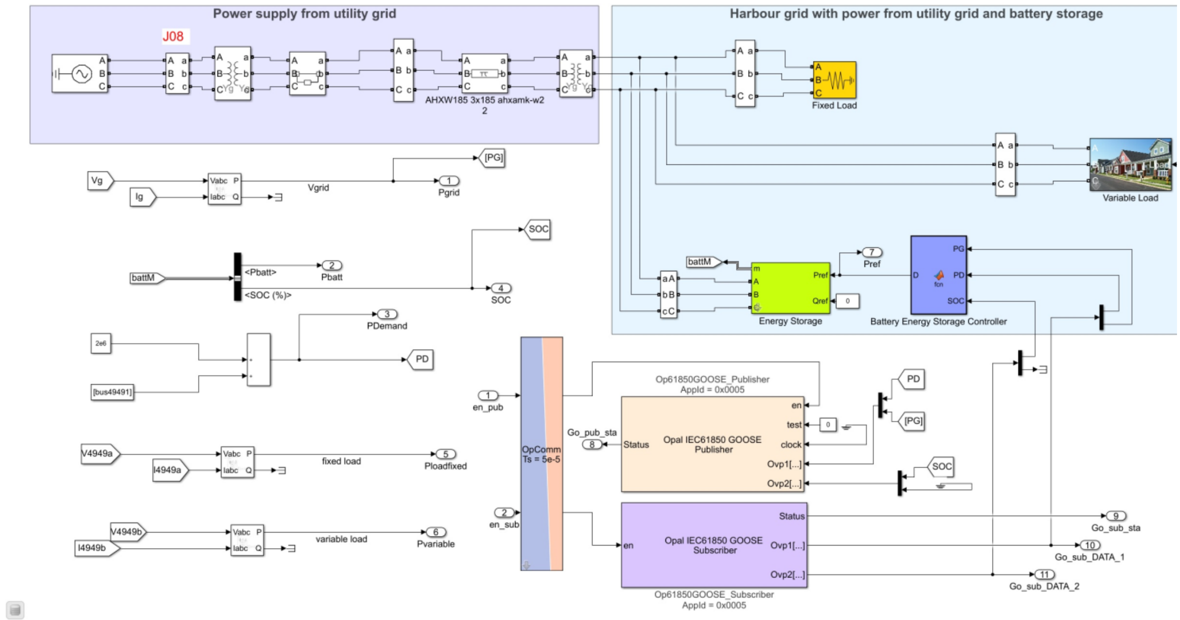

Fig. 1. Computational subsystem model of Vaasa harbour grid


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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>
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       <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">
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    <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.

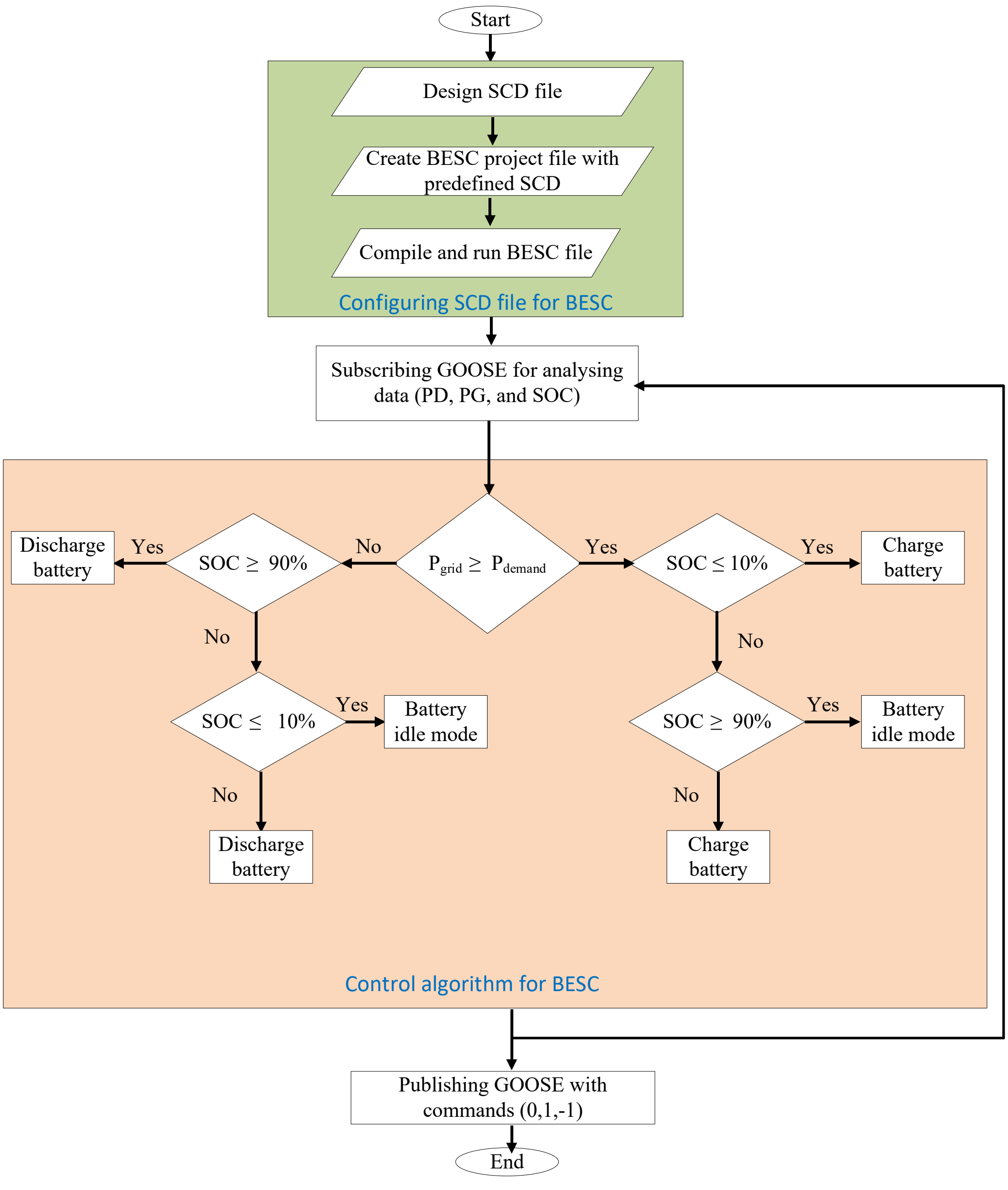

Fig. 3. BESC algorithm using IEC61850 GOOSE message

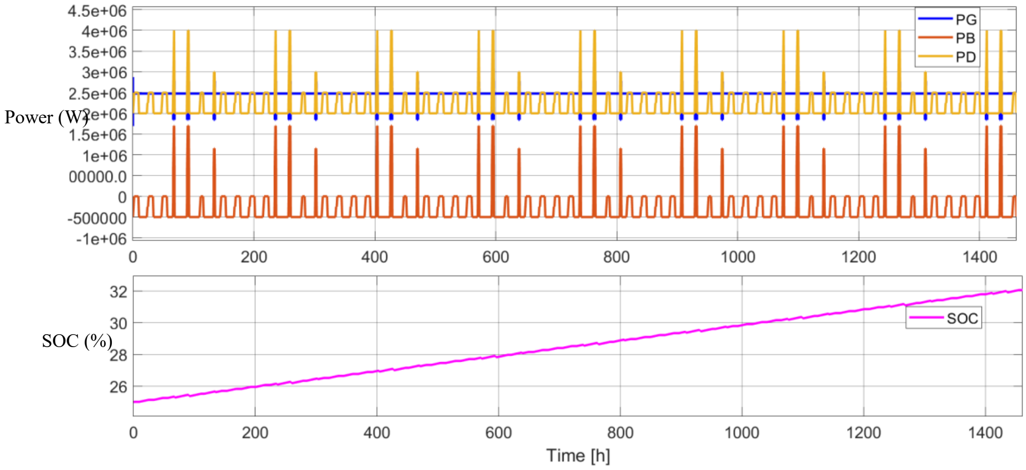

Fig. 4. Battery energy storage at SOC=25%

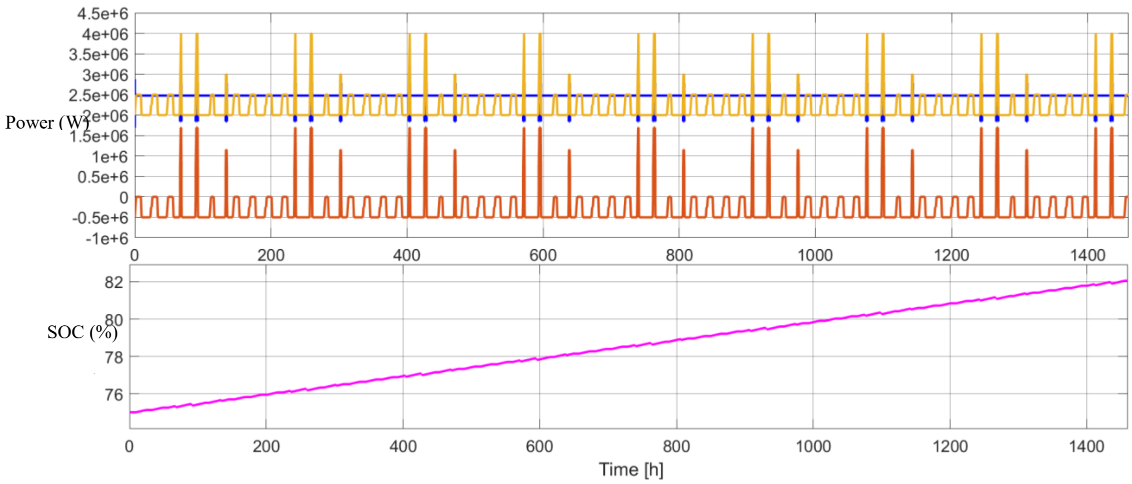

Fig. 5. Battery energy storage at SOC=75%

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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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

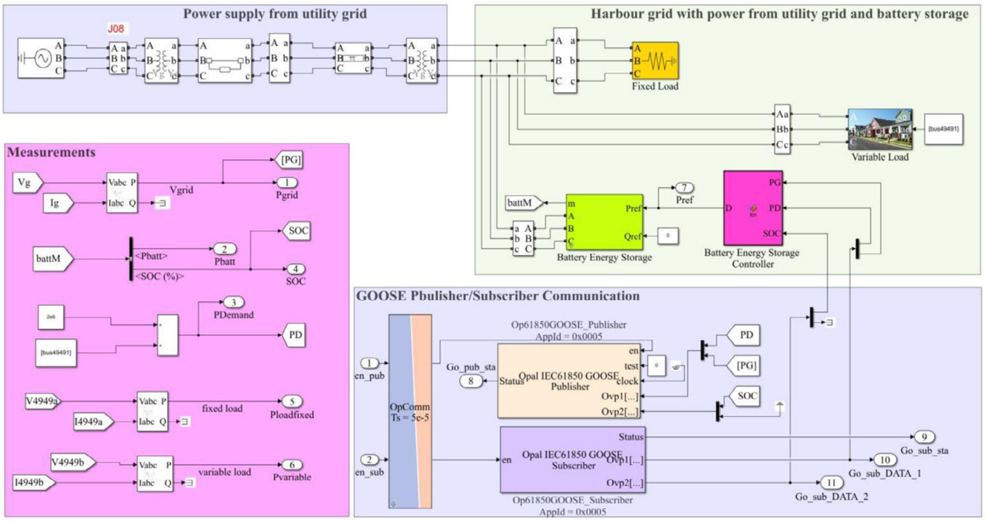

Fig. 1. Computational subsystem model of Vaasa harbour grid [27].

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.

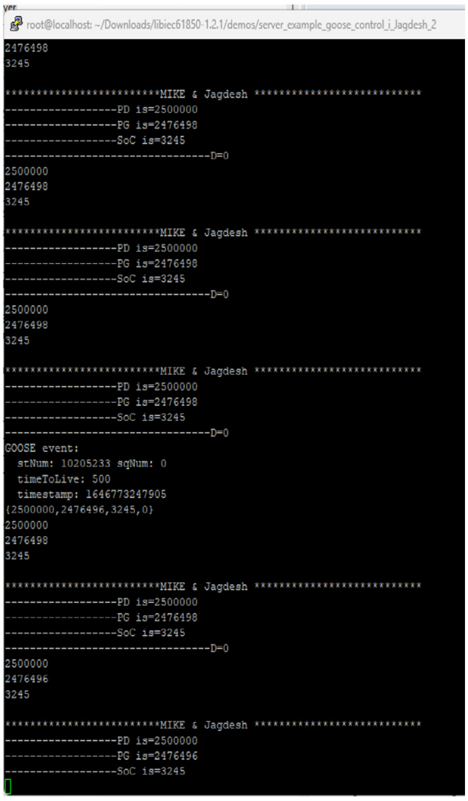

Fig. 2. SSH terminal of IEC 61850 GOOSE parameters and extracted measurements from BESC.

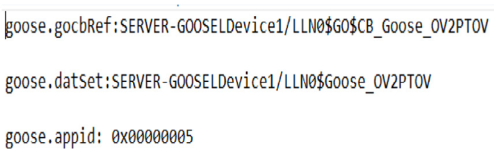

Fig. 3. IEC61850 GOOSE block subscriber parameters.

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

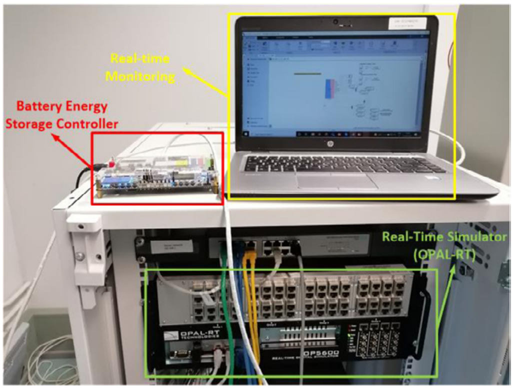

Fig. 4. HiL experimental setup for the BESC implemented in the FPGA board.

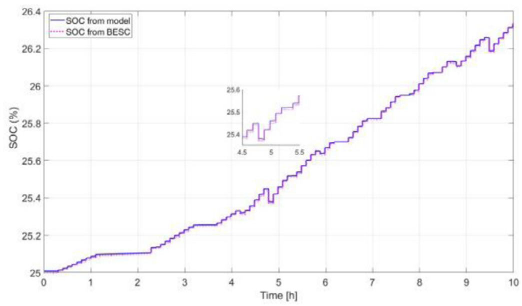

Fig. 5. Comparison of SOC = 25% from BESC and model.

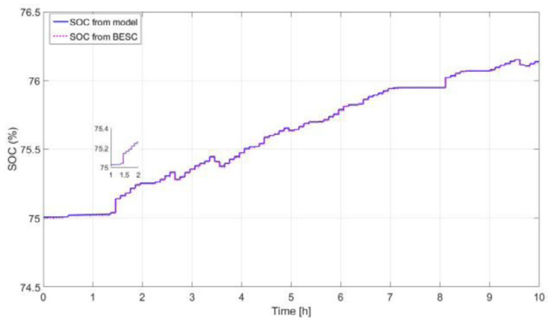

Fig. 6. Comparison of SOC = 75% from BESC and model.

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.

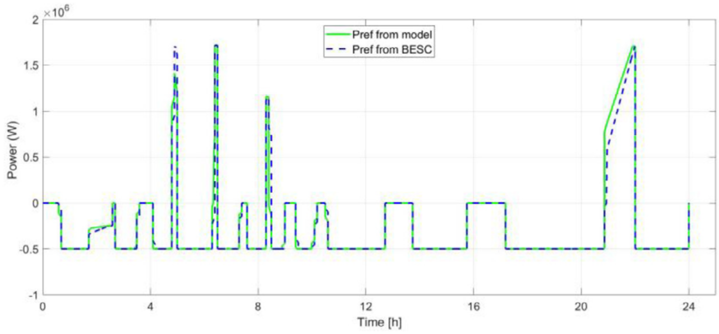

Fig. 7. Comparison P_{ref} from model and BESC.

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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