Granaune, Daniel Andreassen
Prytz, Berge Kierulf
Jensen, Thomas

Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Marine Technology

Battery integration for retrofit electrification of marine vessels;

With a case study of the NTNU Research Vessel Gunnerus

Master's thesis in Marine Technology
Supervisor: Mehdi Zadeh
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Abstract

Increasing environmental concerns, such as rising global temperatures and more extreme weather conditions, drive the maritime industry to reduce its greenhouse gas emissions. Currently, the maritime industry accounts for approximately 3% of global greenhouse gas emissions. To address the escalating climate change problem, innovative and efficient solutions are necessary to achieve international climate goals.

Electrification of marine vessels and the installation of onboard battery systems have emerged as promising solutions to reduce fossil fuel usage and greenhouse gas emissions. This thesis investigates factors related to the integration of battery energy storage systems in hybrid ships, mainly focusing on retrofit applications. These factors are then applied to the NTNU research vessel, Gunnerus. Installing a battery energy storage system on an existing hybrid vessel is a complex process with many interconnected elements, where a single decision can impact multiple aspects of the project. Currently, there is no standardized method for installing a battery energy storage system on a ship, and this thesis contributes with an overview of critical considerations in the early stages of retrofit battery integration.

The pre-conceptual project analysis focuses on understanding the desired outcomes and identifying retrofit constraints. It is essential to recognize the opportunity space and comprehend the stakeholders' motivations. Technical data of the use case vessel are examined, and AIS data are analyzed to understand its normal operations and define its operational modes. In the concept design, the potential of a battery energy storage system is evaluated from a technical perspective. This includes assessing available space and proposing a sizing strategy based on the vessel's load profiles, energy and power demands, and battery state of charge range. Fuel savings for different battery sizes and load profiles are also calculated. The thesis evaluates the appropriate lithium-ion battery chemistry and proposes some state-of-the-art grid options.

The preliminary design is divided into three aspects of the retrofit: physical, electrical, and control integration. Physical integration covers battery design, placement, hydrostatic evaluation, and safety management. Electrical integration focuses on the power distribution system and incorporating the battery into the existing electrical grid, addressing challenges like power quality and grid protection. Control integration proposes a systematic approach to achieve the desired outcomes and tests the feasibility of the control system architecture through Simulink simulations.

Installing a 1 MWh battery system on RV Gunnerus can reduce fuel consumption by 21.4% on a typical voyage. This result is derived from an analysis of AIS data from 2023, load profiles extracted from two different voyages, and specific fuel consumption curves calculated from the same datasets. Additionally, the proposed control architecture, which includes a DC-bus connecting the propulsion's DC links in the variable speed drives and a small active front-end converter linking the DC-bus to the AC-bus, allows the retention of existing passive diode rectifiers. By directly controlling the battery's DC-DC converter, the behavior of the diesel generators can be indirectly managed.

Summary Norwegian

Økende miljøbekymringer, som stigende globale temperaturer og mer ekstreme værforhold, driver den maritime industrien til å redusere sine klimagassutslipp. Den maritime industrien for omtrent 3% av de globale klimagassutslippene. For å adressere det økende klimaproblemet, er innovative og effektive løsninger nødvendige for å nå internasjonale klimamål.

Elektrifisering av maritime industrien og installasjon av batterisystemer ombord har vist seg å være lovende løsninger for å redusere bruk av fossilt brensel og redusere klimagassutslipp. Denne oppgaven undersøker faktorer knyttet til integrering av batterisystemer i hybride skip, med hovedfokus på ettermontering. Disse faktorene anvendes deretter på NTNUs forskningsfartøy, Gunnerus. Å installere et batterisystem på et eksisterende hybridfartøy er en kompleks prosess med mange sammenhengende elementer, hvor en enkelt beslutning kan påvirke flere aspekter av prosjektet. For tiden finnes det ingen standardisert metode for å installere et batterisystem på et skip, og denne avhandlingen bidrar med en oversikt over kritiske betraktninger i de tidlige stadiene av ettermonterings-prosessen av batterier.

Den pre-konseptuelle prosjektanalysen fokuserer på å forstå de ønskede resultatene og identifisere begrensninger. Det er essensielt å gjenkjenne mulighetsrommet og forstå partenes motivasjoner. Tekniske data for RV Gunnerus undersøkes, og AIS-data analyseres for å forstå dets normale operasjoner og definere dets operasjonsmønster. I konseptdesign evalueres potensialet for et batterisystem fra et teknisk perspektiv. Dette inkluderer vurdering av tilgjengelig plass og forslag til en størrelses-strategi basert på fartøyets lastningsprofiler, energi- og effektetterspørsel, og batteriets ladeintervall. Drivstoffbesparelser for forskjellige batteristørrelser og lastningsprofiler beregnes også. Oppgaven vurderer passende litium-ion batterikjemi og foreslår noen topp moderne skipsnett alternativer.

Forprosjektet er delt inn i tre aspekter av ettermonteringen: fysisk, elektrisk og kontrollintegrasjon. Fysisk integrasjon dekker batteridesign, plassering, hydrostatisk evaluering og sikkerhetsstyring. Elektrisk integrasjon fokuserer på kraftdistribusjonssystemet og integrering av batteriet i det eksisterende elektriske nettet, og tar for seg utfordringer som strømkvalitet og nettbeskyttelse. Kontrollintegrasjon foreslår en systematisk tilnærming for å oppnå de ønskede resultatene og tester gjennomførbarheten av kontrollsystem-arkitekturen gjennom Simulink-simuleringer.

Å installere et 1 MWh batterisystem på RV Gunnerus kan redusere drivstofforbruket med 21,4 % på en typisk reise. Dette resultatet er avledet fra en analyse av AIS-data fra 2023, lastningsprofiler hentet fra to forskjellige reiser, og drivstofforbrukskurver beregnet fra de samme datasettene. I tillegg tillater den foreslåtte kontrollarkitekturen at man beholder de eksisterende passive diodelikeretterne. Videre inkluderer arkitekturen en DC-skinne som kobler fremdriftens DC-lenker, og en liten aktiv front-end omformer som kobler DC-skinnen til AC-skinnen. Ved å direkte kontrollere batteriets DC-DC-omformer kan oppførselen til dieselgeneratorene indirekte styres.

Preface

This master's thesis was conducted at the Department of Marine Technology at the Norwegian University of Science and Technology (NTNU). It marks the final part of our Master's degree in Marine Technology with the main profile of marine engineering.

It has been an educational process since we started working on the specialization project in the autumn of 2023. Some parts of this thesis are based on the work we started there.

We want to thank our supervisor, Professor Mehdi Zadeh, for regular meetings and excellent guidance regarding our work. We would also like to express our gratitude to Ph.D. Candidate Marius Ulla Hatlehol for his assistance as a co-supervisor and our discussions regarding power electronics and Matlab simulations. Thanks to Professor Dong Trong Nguyen for his work as a co-supervisor and for his contributions to our regular meetings with Professor Mehdi Zadeh.

We would also like to express our gratitude to Sten Terje Hovden-Falnes and Jesper James Cook Norum, the captain and the chief of RV Gunnerus, for their help and insight about the vessel.

We also extend our gratitude to Senior Research Scientist Olve Mo at Sintef for taking the time to discuss the approach to designing the energy management strategy.

Finally, we express our gratitude to the FLEXSHIP project for allowing us to follow them and learn from their process and discussions via video calls on Teams.

Berge Matre Prytz

Daniel Granaune Andreasen

Thomas Jensen

June 6, 2024

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List of abbreviations

AFE active front end

AIS automatic identification system

AVR automatic voltage regulator

BESS battery energy storage system

BMS battery management system

CC/CV constant-current constant-voltage

DNV Det Norske Veritas

DP dynamic positioning

EMSA European maritime safety agency

EMS energy management system

ESS energy storage system

GHG green house gas

HAZID hazard identification

IEC International Electrotechnical Commission

IEEE Institute of Electrical and Electronics Engineers

IMO International Maritime Organization

LFP lithium iron phosphate

LEL lower explosive limit

LTO lithium titante oxide

LV low voltage

MCR maximum continuous rate

MEPC marine environment protection committee

MT1 trim moment

MV medium voltage

NEMA National Electrical Manufacturers Association

NMC nickel manganese cobalt

NTNU Norwegian University of Science and Technology

PMS power management system

PMS/EMS power/energy management system

PQ power quality

RMS root mean square

S2S shore-to-ship connection

SFC specific fuel consumption

SLD single line diagram

SOG speed over ground

SOC state of charge

SOH state of health

SSCB solid-state circuit breakers

THD total harmonic distortion

TPC tonnes per centimeter immersion

VCG vertical center of gravity

VSD variable speed drive

1 Introduction

1.1 Background and motivation

In the Paris Agreement from December 2015, 195 countries agreed to keep the global rise in average temperature well below 2 °C compared with pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels [1]. The maritime industry is responsible for a significant amount of green house gas (GHG) emissions and substantially contributes to the climate change problem. More than 3% of global GHG emissions can be attributed to ocean-going ships [2].

The maritime industry is undergoing a technological transition aimed at increasing the use of carbon-neutral fuels. A significant trend has been observed in vessels built with alternative propulsion systems designed to lower fuel consumption and GHG emissions. This trend is mainly driven by the international community and the increasing number of regulations focused on climate-friendly solutions [3].

As a consequence of the Paris Agreement, the International Maritime Organization (IMO) developed a strategy for the decarbonization of the sector [4]. The latest edition is the "*2023 IMO Strategy on Reduction of GHG Emissions from Ships*". This document sets more ambitious targets to address harmful emissions and climate change than seen previously [5], as agreed upon at the 80th session of the IMO's marine environment protection committee (MEPC). The revised strategy aims to drastically reduce GHG emissions in international shipping, aiming to achieve net-zero emissions by 2050. The interim goals are at least a 20% reduction in emissions, aiming for 30% by 2030, and at least a 70% reduction, aiming for 80% by 2040, both compared to 2008 levels [5]. To achieve this, reviewing the pollution from the maritime industry is necessary, and hybrid solutions for ships have proven to be a viable option [6]. The benefit of installing an energy storage system (ESS), such as batteries, flywheel, and supercapacitor, is not limited to new ship builds. The number of retrofits to existing vessels is approximately ten times higher than the number of new ships being built [7]. Retrofitting a vessel involves updating or modifying parts of it to include new technologies, systems, or features that it originally did not have, or to comply with new regulations. Hence, it is essential to also focus on retrofits from an environmental perspective.

Previous research on battery installation in offshore support vessels indicates that the annual global warming potential could be reduced by approximately 40-45% in Arctic areas, while the reduction in the North Sea is estimated at 20% [8]. The environmental advantages are significant, but the economic benefits depend on the total cost. The payback time of retrofitting a vessel with a battery is estimated to be 10-15 years, according to Lindstad et al. [8]. Considering the ship is at some age before the retrofit, it might not benefit the shipowner economically. Two factors may increase the economic advantages of retrofitting. First is international regulations that increase the pressure of carbon-neutral power systems, increasing the penalty of only having combustion engines, thus reducing the relative cost of retrofitting. Second, the technology used in battery integration, which stretches from battery technology to efficiency in the control system, can improve so that the economic benefit is improved.

The EU project, FLEXSHIP, is a research project with an overall goal to develop and validate safe and reliable, flexible, modular, and scalable solutions for electrification of the waterborne sector [9]. In other words, the FLEXSHIP project aims to improve the technology used in battery integration and make it less complicated to implement for a wide range of vessels. FLEXSHIP is a multidisciplinary initiative aimed at advancing maritime technology and sustainability. The project states that they will demonstrate innovations that go beyond the state-of-art for the following elements: green digital twin, safe integration of large batteries, safe and reliable battery systems, monitoring of system operations, and strategy for long-term skills' development [9]. Further on in the project, FLEXSHIP will use NTNU's research vessel Gunnerus to show that their concepts are practical. This master thesis will investigate battery integration in a vessel retrofit, with RV Gunnerus as a use case.

1.2 Overview of battery integration; safety, sizing, architecture and control management

Regarding maritime battery energy storage system (BESS), lithium-ion batteries are predominant due to their high energy density, longer lifespan, and low maintenance [10], but there are some safety challenges. The biggest concern related to safety with the integration of a lithium-ion BESS onboard a vessel is thermal runaway, which is a self-propagating exothermic reaction within a lithium-ion battery [11], potentially causing smoke, fire, and even explosions [10]. To overcome this concern, a reliable thermal runaway propagation system is required. This includes a ventilation system, correct firefighting equipment, and routines for preventing dust and other foreign materials from entering the battery space [12]. The thermal management system ensures the battery operates at the right temperature by regulating the cooling or heating flow [13]. Additionally, the thermal management system may have a protective function to cool the batteries in the event of a temperature rise, where the risk of thermal runaway is heightened. The system might utilize either air cooling or liquid circulation. To enhance lithium-ion battery safety and mitigate the risk of thermal runaways, extensive research has been conducted on various strategies to prevent thermal runaways and effective methods to contain any initial fire outbreak.[10, 11, 13]. The primary aspect of thermal runaway safety involves the battery management system (BMS), which monitors battery cells for temperature, load, and charge levels. The aim of the BMS is to safeguard the battery against short circuits, overloads, overheating, overcharging, and excessive discharge, as these factors could potentially lead to thermal runaway.

A significant number of research papers have focused on determining the optimal BESS size for specific vessels or vessel types [14–17]. In [14], a sizing strategy for an all-electric tugboat for short voyages was presented; however, the strategy required a substantial amount of data for the specific vessel. It utilized hydrostatic data and speed power analysis to determine the effective power required to operate at 9 knots and also designed a suitable propeller for this operating condition. The article [15] concluded that the cost-benefit index was proportional to the BESS lifetime but not to BESS sizing. This indicated that installing a moderately sized BESS and optimizing its usage was more economical than aiming for enhanced fuel savings through strategic loading and investing in a larger BESS to diminish cycling stress and extend its lifespan. The study also emphasized that the performance of the BESS was strongly dependent on the operational profile of the vessel and the chosen energy management strategy for the BESS. The two presented articles were strongly reliant on data from the specific vessel. Furthermore, the articles did not consider the non-quantified parameters; the stakeholders, rules, and regulations may affect the optimal battery size. Essential retrofit factors, such as physical constraints and battery degradation, were not considered. Bordin and Mo [16] proposed an optimization model for battery sizing where degradation, weight, and space were considered constraints. However, it did not consider the stakeholders and required relatively heavy calculations. The Maritime Battery Forum has proposed an iterating process on how to size and select maritime batteries [17]. This was not a quantified model but illustrated the important factors to take into account. It was stated that it is an iteration process regarding the following elements: define the operational profile, determine the four main requirements for the battery, select the right sizing strategy, and find the right fit. This strategy included the non-quantified factors; however, it did not result in an optimal size for the battery in terms of kWh. Choosing between these strategies was, therefore, dependent on available data and objectives from the stakeholders.

Contemporary marine vessels require an electric power distribution system. The ship's electrical grid connects energy producers with consumers and can also include energy storage solutions. The grid is built to function independently as a self-sufficient system, the power is either immediately used, stored for later, or dissipated. The main switchboard is typically divided into two, three, or four sections to meet the vessel's redundancy needs. Electrical propulsion regulations dictate that the system should withstand the failure of one section, such as from a short circuit. For the highest levels of redundancy, the system should also be resilient to fire and flooding, necessitating fire-resistant and waterproof barriers between sections [18]. These regulations depend on various factors, including the type of vessel, type of operations, and class society. Typically, the main switchboard is AC, but it is also possible to have a DC grid. Several research articles on AC and DC distribution systems onboard marine vessels show a favorable inclination towards DC distribution systems. Many studies also highlight several challenges associated with the adoption of DC distribution systems, and while promising, they have not yet become widespread in the maritime industry [19–21]. The article [19] gives a comprehensive overview of the history and development of electric power systems on several vessel types, including state-of-the-art technology and future trends. It stated that DC distribution systems have great potential, especially with DC energy sources such as batteries or fuel cells, and will likely be used more in the future. It does not simulate or apply tests to a specific use case. In [20], it is also shown that it is advantageous with DC power distribution rather than AC when the vessel uses DC energy storage systems. In [21], it is emphasized that the main benefits of a DC distribution system are the freedom of frequency, resulting in no reactive power, simplifications of the variable speed drive (VSD) for motor control, and easier integration of DC power sources. It also notes that the DC distribution system still has some challenges, like instability under constant power loads, and more complex mechanisms are needed to extinguish large fault currents safely.

For the BESS to function properly, there has to be a well-functioning control system. The purpose of a control system is to coordinate different energy sources according to the current load demand. The main goal is to achieve optimal energy distribution in a secure way by building suitable energy management system (EMS), power management system (PMS), and BMS [22]. There are several techniques to establish a control system, but the two main categories are an optimization-based control system and a rule-based system. In contrast to rule-based methods, optimization-based EMS/PMS approaches can provide more effective solutions and are increasingly prevalent in use today [23]. While an optimization-based control system tends to prove the benefits of this technique, it often does not consider the regulations and requirements from class societies related to the ships' operation. A review and discussion around the different optimization-based methods can be found in [23] and [24]. A rule-based control strategy in the real world is most commonly found in hybrid vehicles with a combustion engine and a battery, which is also reflected in the literature. A rule-based control system is sometimes seen as an outdated strategy, as the solution may not be optimal. However, [25] proved that it is still relevant in energy management systems; Wang explored a rule-based system for a hybrid vehicle with a fuel cell, battery, and supercapacitors, and concluded that the rule-based system improved both fuel consumption and dynamics. Another factor to consider when choosing a strategy is computational time. In [26], a rule-based strategy was compared with the optimization-based strategy of dynamic programming, finding that the computation time for 35 simulations of a hybrid vehicle was 56 hours for optimization-based, compared to less than 1 minute with a rule-based approach. The optimization-based strategy offers the optimal solution at the expense of computation time and limited flexibility. The rule-based strategy offers excellent flexibility and reliability but does not necessarily provide the optimal solution.

1.3 Objectives and scope

The main objective of this thesis is to investigate lithium-ion battery integration in a vessel retrofit, in terms of physical integration, electrical integration, and control integration with a focus on RV Gunnerus as a use case. This will contribute to the FLEXSHIP project regarding BESS integration. It will not be an actual part of the FLEXSHIP project, but it will be a contribution regarding feasible solutions and important factors to consider in a retrofit project, exemplified through the use case of RV Gunnerus.

Most of the current literature on battery integration aims to find the optimal solution, as illustrated in subsection 1.2. The techniques and strategies reviewed, require detailed technical knowledge about the vessel and its components. However, the demands and requirements of stakeholders and class societies are often not considered. In practice, these considerations tend to be paramount. This thesis will, therefore, prioritize a reliable and flexible solution over an optimal one. Moreover, stakeholders and class societies play a more significant role in the integration process.

It is important to define and understand the constraints, possibilities, and stakeholders' motivation before looking at the actual BESS integration. The thesis will give an overview of important factors before it investigates the case study of BESS integration on RV Gunnerus.

The scope of the thesis can be summarized with the following:

- Investigate and define important factors with BESS integration. Such as collecting and analyzing ship data, physical capabilities, information on the electrical grid, and load profiles. Information about the different stakeholders, and the motivation for the BESS integration.
- Make a preliminary analysis of battery selection and sizing.
- Analyse potential fuel savings for the use case vessel when implementing a BESS, by making a simulation model of the energy consumption with a BESS and comparing it to historical load data.
- Investigate and analyze feasible solutions for BESS integration on RV Gunnerus regarding physical integration, electrical integration, and a rule-based control integration.
- Propose a BESS integration for the use case vessel. Discuss the uncertainties and possible improvements for the proposed solution.

1.4 Thesis structure

The thesis revolves around the retrofit process of integrating a BESS onboard RV Gunnerus. Retrofitting a vessel involves updating or modifying parts of it to include new technologies, systems, or features that it originally did not have, or to comply with new regulations. The thesis will include a review of literature, rules, regulations, and industry practices to understand the challenges and assess various solutions.

The thesis begins with analyzing the current circumstances aboard the vessel through **Chapter 2: Pre-conceptual concept design**. This chapter is aimed at first conducting an analysis of the vessel and its operational profiles. Moreover, an examination of the stakeholders involved and their objectives concerning the retrofit is conducted. **Chapters 3-6** are structured in a systematic approach inspired by [27], for assessing and refining a vessel retrofit process. These chapters assess battery integration from a technical standpoint. **Chapter 3: Concept design** presents an evaluation of the potential for battery installation on the vessel, thereby validating the concept. This is done through a space analysis, a battery sizing evaluation, and the potential for fuel savings. This chapter is finalized through a grid topology and battery type evaluation. **Chapters 4-6** presents the preliminary design process, evaluating the physical, electrical, and control integration of a BESS. These three aspects forms the battery integration for this thesis, illustrated in Figure 1.2. Each chapter consists of sections on relevant topics. Different methods are presented and assessed for each section from a broad perspective. Subsequently, their results in terms of feasibility are specifically examined in the context of the thesis use case, RV Gunnerus.

- In **Chapter 4: Physical integration**, the design spiral enters the second iteration phase, further evaluating the technical integration of the system into the vessel, first from a physical perspective. The possibilities for placement of the batteries are evaluated, along with the required battery dimensions. Then, the influence on the vessel hydrostatics is evaluated for the different solutions. Finally, requirements for safety management are elaborated.
- **Chapter 5: Electrical integration** evaluates the integration from an electrical perspective. It delves deeper into the power grid topologies and the necessary power converters before evaluating the importance of power quality in ship grids. A presentation on different ways to solve the shore-to-ship connection is presented before a description of power grid protection and selectivity.
- **Chapter 6: Control integration** proposes a systematic approach to achieve the desired outcomes and tests the feasibility of the control system architecture through Simulink simulations.

Chapter 7: Use case recommendations; RV Gunnerus aims to give an overview of the earlier chapters' recommendations, highlighting the specifications of a possible option in terms of a feasible BESS integration onboard.

The following part of the thesis is structured as shown in Figure 1.1.

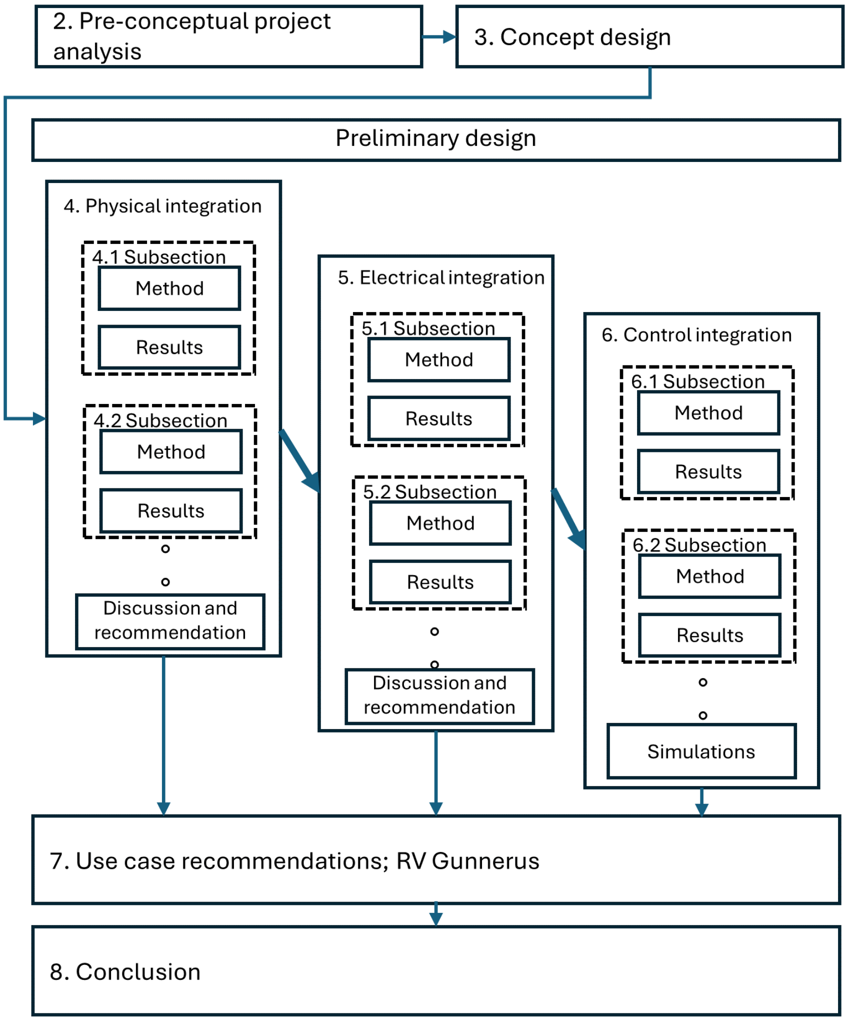


Figure 1.1: Thesis structure.

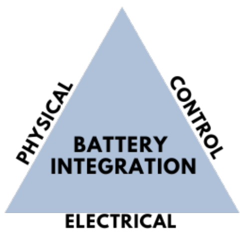


Figure 1.2: Design triangle.

2 Pre-conceptual project analysis

For a successful retrofit project, it is important that the desired outcomes are understood and the constraints identified. A pre-conceptual analysis of the project is necessary to understand these parameters. This analysis aims to set the opportunity space for the project and identify the motivations of the different stakeholders. Firstly, a brief analysis of the specific vessel, RV Gunnerus, is conducted. It aims to map out the operational modes for the vessel, with corresponding load profile and spinning reserve demands. The understanding of this illustrates the potential of battery integration. Furthermore, the stakeholders, class society, and design and approval process are analyzed. Understanding the desired outcome for the stakeholders is crucial for a successful retrofit. An overview of the potential technical advantages of BESS integration is also presented as a motivation for electrification. Lastly, a risk analysis is done to identify and understand the possible hazards in a retrofit project.

2.1 RV Gunnerus: General information

The research vessel Gunnerus, put into operation in the spring of 2006, is owned and operated by NTNU. Primarily, it supports diverse research activities in fields such as biology, technology, geology, archaeology, oceanography, and fisheries research. A standard cruise day for RV Gunnerus is from 8 am to 8 pm [28], mostly operating in the Trondheimfjord, but she can also be used for more extended operations. Conversations with the crew indicate that a normal day at sea involves leaving the harbor in the morning, transiting to a planned location where the vessel goes into dynamic positioning (DP) with minor position changes followed by transit back to the harbor.

The vessel has advanced technological features, including a dynamic positioning system and a high-precision acoustic positioning system known as HiPap 500. This makes it ideal for ROV operations and precise equipment positioning. RV Gunnerus has undergone two significant retrofits. In 2015, it received two permanent magnet azimuth thrusters from the former Rolls-Royce Commercial Marine, and in spring 2019, its midship section was extended by 5 meters. The vessel also includes a bow tunnel thruster. This diesel-electric system is specially designed to produce low hydroacoustic noise levels, which is important for testing and developing hydroacoustic equipment. Inside, the vessel features a wet lab, dry lab, computer lab, and a generous aft deck [28]. The single line diagram (SLD) for RV Gunnerus is presented in Figure 2.2, which will be the starting point of the electrical battery integration.

Figure 2.1: RV Gunnerus port side view. Photo: Berge M. Prytz.

Table 2.1: Capabilities and dimensions of RV Gunnerus, [28], [29].

Feature	**Specification**
Propulsion	Rolls-Royce Azipods 2 x 500 kW
Bow tunnel thruster	Brunvoll 1 x 200 kW
Generators	Nogva-Scania 3 x 450 kW
AC main switchboard	440 V, 60 Hz
Speed at 100% maximum continuous rate (MCR)	12 knots
Cruising speed	10.5 knots
Consumption at cruising speed	Power: 640 kW, Fuel: 160 L/h
Deadweight	411.8 t
Length overall (Loa)	36.25 m
Length between pp (Lpp)	33.90 m
Length in waterline (Lwl)	24.90 m
Breadth middle (Bm)	9.60 m
Breadth extreme (B)	9.90 m
Depth mld. Main deck (Dm)	4.20 m
Draught, mld (dm)	2.70 m

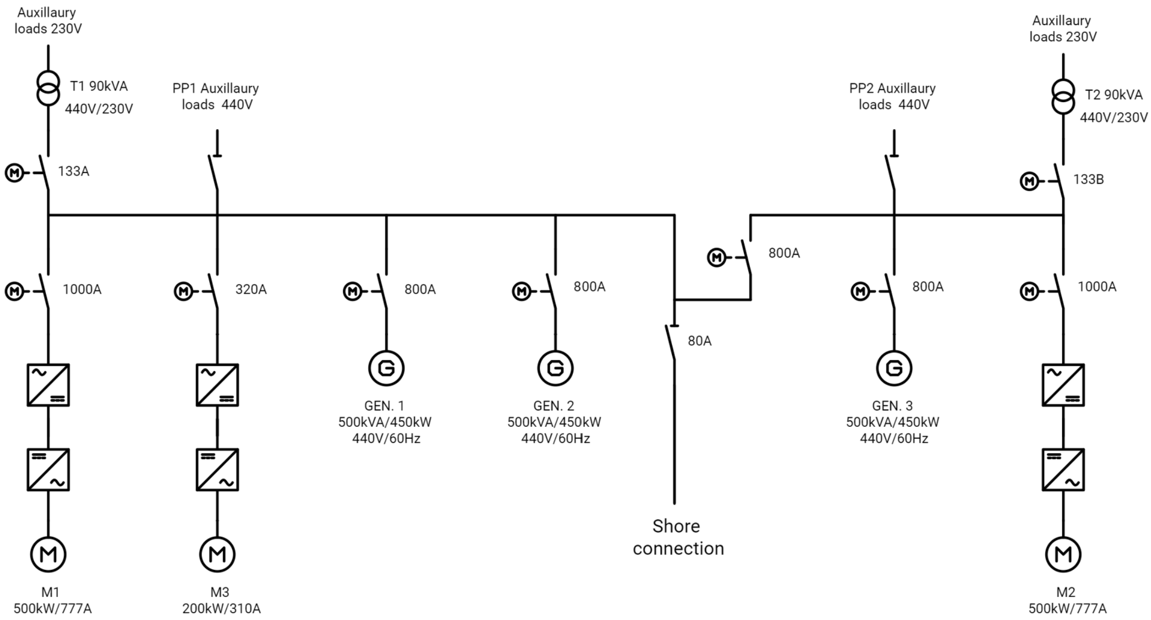


Figure 2.2: Single line diagram for RV Gunnerus.

2.2 RV Gunnerus: Operational modes

Defining operational modes is important for understanding and categorizing how the vessel operates. Studying these modes may reveal the optimal utilization of a battery. The content of the operational modes is determined by the data available. For instance, a newbuild lacks actual data on load demands, whereas such data can be obtained in a retrofit project. Although the content varies, the overall goal is to illustrate how the vessel operates. Operations can be defined based on the ship log, voyage data, or discussions with the crew.

Several interested parties are considered to understand the requirements within each operation. The captain and the crew are responsible for safe operation, so they may have specific requirements for each operation. These requirements, forming the basis of the vessel's operation, must be taken into account. The classification society may impose demands and requirements on the operations. For example, in DP operations, rules regarding redundancy and safety are established by the classification society. The on-board PMS also introduces requirements by starting another generator when the demand reaches a certain limit. An estimation of how much time the vessel spends in each operation and the associated load profile is also of interest.

For the use case, five operations are defined, based on a conversation with the crew [30]: *at harbor*, *harbor maneuvering*, *transit heavy*, *transit calm*, and *DP*. The quality of the gathered data varies, some are based on estimations, while some are based on actual ship data. When the operational modes are being established, awareness of the data quality is important. The data used to form the basis for the load profiles are from two days at sea, on the 21st and 22nd of November 2023, when the vessel was on an assignment with an organization named *Naval Group*. These days RV Gunnerus was on a voyage in Trondheimsfjorden, leaving the harbor in the morning and returning in the afternoon. The average wind was between 2-3 m/s, indicating good weather conditions for DP. The output power of each generator, sampled at 10 Hz, was analyzed with Python to determine the power demand in each operational mode. An overview of the operational modes, including corresponding time, number of running generators, and the average demand, is presented in Table 2.3. Optimally, the data set used could have included more than only two days of operations, on the other hand, the quality of the data and the sampling frequency are good and considered sufficient. In addition to conversations with the crew, automatic identification system (AIS) data of RV Gunnerus was analyzed to determine the time it spends in the different modes yearly.

AIS data

AIS data from the year 2023 for RV Gunnerus was gathered from Kystverket, and the plotted positions are illustrated in Figure 2.3. The data is filtered based on speed and changes in position using Matlab.

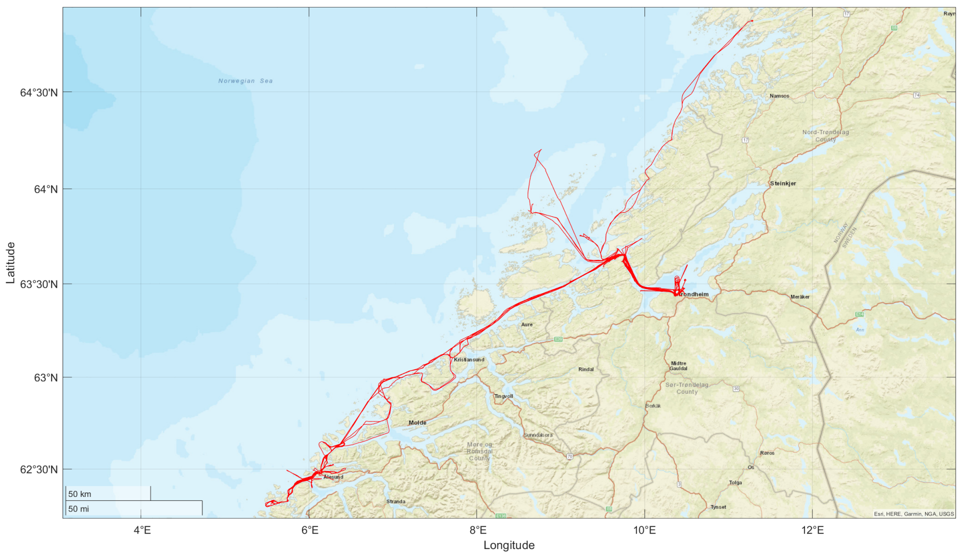
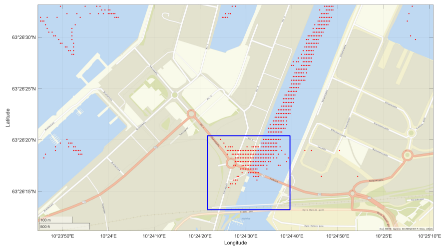
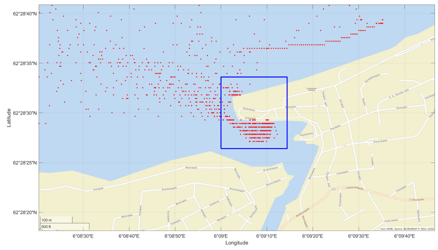


Figure 2.3: AIS positions for RV Gunnerus in 2023.

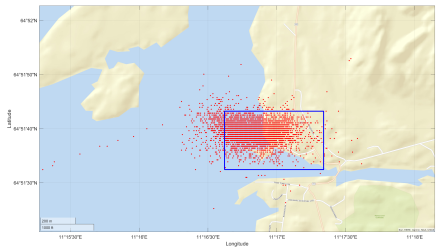
Based on this data, the time spent at the harbor, harbor maneuvering, and at sea can be estimated. Time spent at the harbor is estimated by establishing boxes where RV Gunnerus has been at berth and calculating the time spent inside these boxes where the speed over ground (SOG) is under 1 knot. Time spent in harbor maneuvering is estimated as the time spent inside the boxes where the SOG is over 1 knot. Lastly, the time at sea is estimated to be the time spent outside the boxes. The harbors for RV Gunnerus, represented by the boxes, are in Trondheim, Ålesund, and Ottersøy, and are illustrated in Figure 2.4. The estimated time spent at the harbor, in harbor maneuvering, and at sea is presented in Table 2.2.



(a) Trondheim harbor.



(b) Ålesund harbor.



(c) Ottersøy.

Figure 2.4: Harbors for RV Gunnerus.

Table 2.2: Time spent in different modes.

At the harbor	Harbor maneuvering	At sea
7551.37 h/year	93.77 h/year	1114.79 h/year

Operational mode 0 - At the harbor

The crew reports that RV Gunnerus spends most of its time at the harbor throughout the year, which correlates well with the AIS data. At the pier in Trondheim, they have access to shore power, allowing them to shut down the generators. However, in other ports, this is not always possible, necessitating the continuous operation of a generator to power the hotel load. The load demand at berth is approximately 20 kW, either from a shore connection or an on-board generator. Based on Table 2.2, an annual time at the harbor is approximately 315 days per year. Note that this is the sum of time spent at the harbor, not the number of days RV Gunnerus is not at sea.

Operational mode 1 - Harbor maneuvering

Harbor maneuvering is defined as the operation going to and from the berth. To analyze the required power demand in this mode, an analysis of the docking operations done on October 21 and 22, 2023, is conducted. There is no clear point where harbor maneuvering is over, and transit begins, but it is estimated by studying the generator's output power and the vessel speed. The load profile for harbor maneuvering is presented in Figure 2.5. When operating in this mode, RV Gunnerus does not require high power for propulsion, and a single generator would suffice. However, to ensure adequate backup power and maintain maneuverability in the event of a generator failure, it is necessary to keep two generators running. Based on Table 2.2, harbor maneuvering accounts for 7.8% of the time when RV Gunnerus is not at berth.

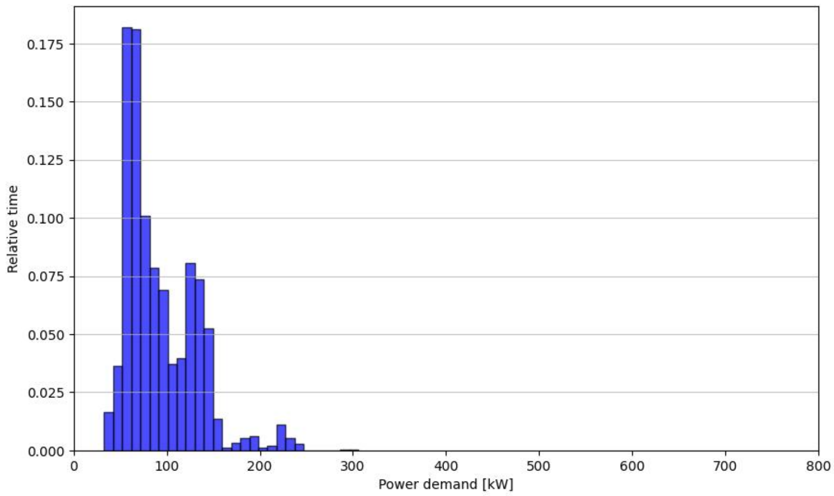


Figure 2.5: Power demand harbor maneuvering.

Operational mode 2 - Transit

RV Gunnerus normally operates in two transit modes, both optimized to achieve the best fuel efficiency. For calm seas, they run two generators and set the RPM slightly below the level required before the third generator would need to start up. The same technique is applied when they transit in rough seas; however, the propulsion control is set to power mode to cope with the variable power demand in rough seas. Sailing in power mode results in a more stable power demand from the pods, but the vessel speed may vary more compared to RPM mode. For this thesis, the two transit modes are considered as one. In Figure 2.6, a histogram of the load profile for RV Gunnerus in transit mode is presented. The power demand is the total generated power for propulsion and hotel loads. To estimate how much time RV Gunnerus spends on transit, an estimation is done based on the AIS data. Time spent outside the harbor boxes, where the SOG is greater than 5 knots, is defined as transit time. If RV Gunnerus were to transit at lower speeds, the load profile would be closer to the defined DP load profile than the transit load profile. Based on this estimation, the relative time spent in transit mode is 28.6%, representing the time spent in transit when RV Gunnerus is not at berth.

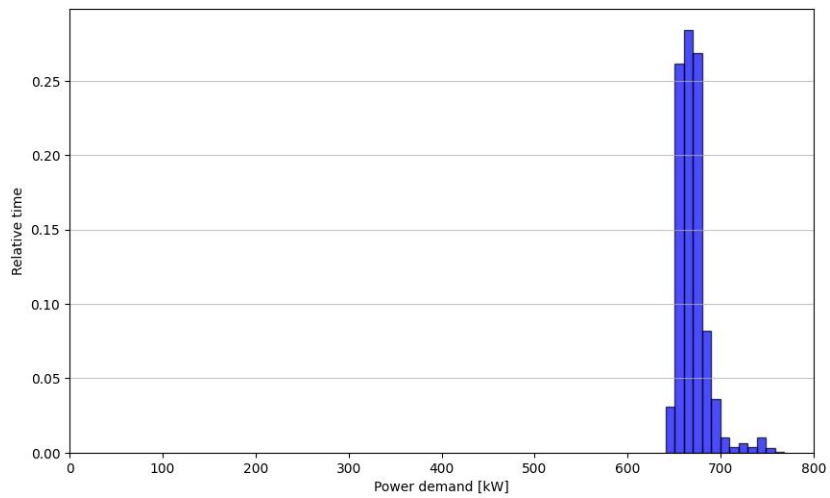


Figure 2.6: Power demand transit.

Operational mode 3 -Dynamic positioning

The last operation mode is DP, a system that automatically maintains the vessel's position and heading using its own thrusters and propulsion pods. This is achieved through a computer-controlled system that continuously adjusts the vessel's propulsion and thrusters based on data from position reference systems, gyrocompasses, wind sensors, and other instruments. A histogram of the load profile for RV Gunnerus is presented in Figure 2.7. In DP mode, one generator would normally suffice to power the hotel load and the required power demand for the DP system. However, due to redundancy requirements, this operation has two generators running. The required redundancy and safety under DP operations varies depending on the class and the ongoing kind of DP operation. For RV Gunnerus, there are no DP class requirements. However, to ensure adequate backup power and maintain maneuverability in the event of a generator failure, it is necessary to keep two generators running according to the crew. The remaining relative time is spent in this mode, accounting for 63.6% of the time spent at sea.

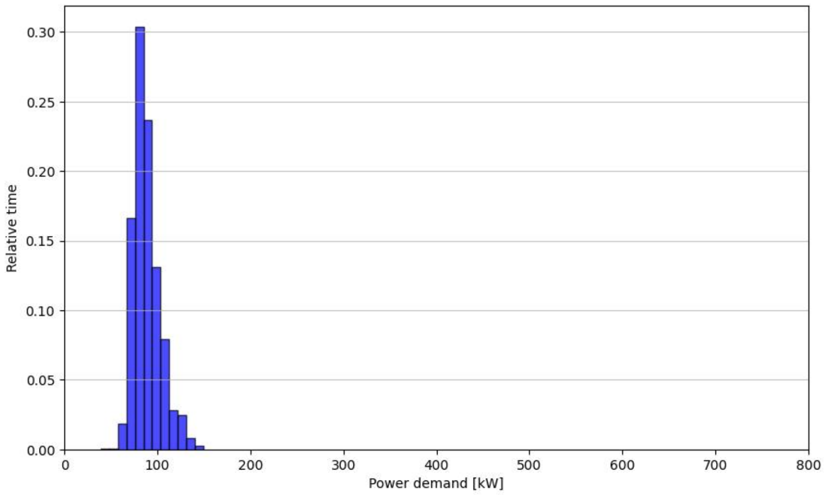


Figure 2.7: Power demand DP.

Table 2.3: RV Gunnerus operational modes.

Mode	Activity	Total time [days/year]	Relative time at sea	Average demand [kW]	Production
0	Harbor	315	n/a	20	shore/1 gen
1	Harbor maneuvering	15	0.078	124	2 gens
2	Transit		0.286	670	2 gens
3	DP		0.636	90	2 gens

2.3 Stakeholders

To understand the desired outcomes of a retrofit, it is important to understand the stakeholders involved. This could be motivated by environmental compliance, energy efficiency, updated usage, or safety and security enhancements. In this process, vessel stakeholders are considered as an essential part. A stakeholder is any individual, group, organization, or entity that has an interest in, is affected by, or can affect the project or the outcome of the project. This includes shipowners and operators, charters, port authorities, class societies, flag states, and more. These diverse stakeholders will have varied priorities and perspectives regarding the desired outcomes of a project. A general illustration of important stakeholders regarding marine vessels and the shipbuilding or retrofit process can be seen in Figure 2.8.

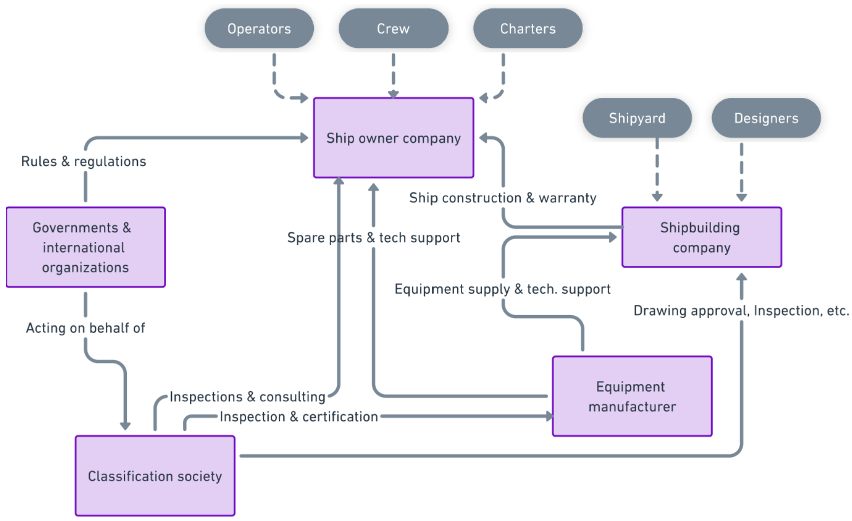


Figure 2.8: Complexity and interconnections between stakeholders in a shipbuilding/retrofit process.

Generally, the process of aligning objectives with a retrofit is typically initiated by shipowners or ship operators. The process is initiated with their idea of desired outcomes, leading to the development of a list of requirements. This list is refined as expertise and perspectives are contributed by every party involved in the process.

Flag state refers to the country where a ship is registered and is responsible for ensuring that vessels comply with international and national maritime regulations. These responsibilities include the enforcement of safety and environmental standards, the conduct of regular inspections, the assurance of maritime security, the upholding of labor standards, and the investigation of marine incidents [31]. The role of the flag state is critical in maintaining the legality, safety, and efficiency of maritime operations, affecting everything from the vessel's operational capabilities to the welfare of its crew. The classification societies, another stakeholder, are tasked by the flag state with the enforcement and verification of ship systems, reclassification, and compliance with international and/or national statutory regulations [32].

A classification system is used to classify ships based on their design, size, type, purpose, and sometimes cargo. Classification societies carry out this classification. These organizations are tasked with establishing and applying technical standards for designing, constructing, and surveying marine-related facilities, including ships. Both the certification of ship design and construction specifications and the regular inspection of ships to ensure compliance with these standards over time are involved in the classification process [33]. Classification by class society is typically required for ships if they are engaged in international trade, must meet specific regulatory requirements, or require certification for insurance purposes.

To obtain a class notation for a ship retrofit, detailed plans, including technical specifications, are initially submitted by the shipowner to the classification society for a preliminary assessment. The retrofit's technical and regulatory viability may be evaluated through a feasibility study. A detailed review of engineering designs and documentation is then conducted to ensure adherence to all applicable standards and regulations. Once the plans are approved, supervision of the retrofit work is carried out by the classification society to confirm matching with the approved specifications. Upon completion, the retrofit is subjected to testing and trials to verify system operations and performance. The issuance of a new class notation results from successful completion and testing. The vessel then remains under continuous survey by the classification society to ensure ongoing compliance with classification standards, encompassing periodic inspections and surveys [33].

Another key stakeholder comprises the ship operators and managers responsible for the vessel's daily operation and whose work will be directly impacted by the retrofit. They should be included in the retrofit process to ensure the retrofit meets operational requirements. The crew would also be considered an important stakeholder, and together with the operators, they possess the most accurate operational knowledge about the vessel. Furthermore, the crew's well-being and efficiency of operations post-retrofit are essential considerations.

RV Gunnerus: Stakeholders

For the retrofit of RV Gunnerus with the integration of a BESS, there are multiple stakeholders. An important stakeholder, the vessel's registered owner, is NTNU. Equipped with various laboratory facilities and equipment for sea surveys, RV Gunnerus serves as a research vessel. Preserving these features throughout the retrofit process is a natural concern for NTNU. Nevertheless, NTNU is also motivated by the possibility of reducing operational costs and increasing operational redundancy by implementing a BESS. With its funding primarily received from the government, NTNU is committed to maintaining its status and reputation. NTNU is a leading institution in various technological fields. Furthermore, environmental sustainability is important. The retrofit of RV Gunnerus can not only demonstrate state-of-the-art technology but also give a more sustainable profile for the vessel and in terms NTNU as an organization.

Within NTNU, there is a board working as the ship operators deciding on the optimal usage for RV Gunnerus and how to prioritize different usage. This board, in addition to the crew, has the best understanding of the current operational modes and best options to install a BESS. It is vital to include them as an important stakeholder. Furthermore, it is important to note that the initiative for this retrofit does not originate from NTNU, but rather from an EU-funded research project called FLEXSHIP.

The FLEXSHIP project, [9], consists of 16 diverse partners from nine countries within the European Union and the UK, and is a multidisciplinary initiative aimed at advancing maritime technology and sustainability. FLEXSHIP focuses on enhancing the maritime sector's transition towards climate neutrality. It aims to do so by developing and implementing flexible and modular large-scale battery systems for safe integration and operation in various types of ships. The project's approach includes creating a green digital twin for designing efficient vessel electrical grid architectures and integrating large-capacity battery systems into existing vessel power grids. This initiative emphasizes creating compact, low-weight, and high-efficiency battery systems to ensure safe onboard integration and interoperability. NTNU contributes to this project by providing expertise in sustainable maritime power systems and making their research vessel, *RV Gunnerus* [28], available as the first demo project. The system's demonstration will entail a multi-layered verification process, including the modeling and simulation of the battery system optimized for the specific needs and specifications of each demo, lab testing of the system on a small scale, and the demonstration of the entire system onboard the demos in sea trials and dockside tests. The goal of the FLEXSHIP project as stated on their web page:

The overall goal of FLEXSHIP is to develop and validate safe, reliable, flexible, modular, and scalable solutions for the electrification of the waterborne sector [9].

The FLEXSHIP program encompasses several goals, and the installation of a BESS on RV Gunnerus is only a way to prove their concepts. Their goal is to achieve the retrofit in a manner that is safe, reliable, flexible, modular, and scalable. *Safe* implies compliance with rules and regulations, while *reliable* refers to consistent functionality and robustness under adverse conditions. Achieving these goals while also being innovative and utilizing state-of-the-art technology presents a significant challenge. *Flexible* means that the solutions should be applicable, not only to RV Gunnerus but also to similar ships. Using modular components can aid in achieving flexibility and scalability, though it may pose challenges in terms of space utilization. Furthermore, FLEXSHIP's aim with this program is not to generate profit, as it is not driven by commercial interests. However, the final solutions must be economically beneficial for future ships, as this aligns with the broader goal of electrifying the waterborne sector. Lastly, and most tangible, FLEXSHIP states that RV Gunnerus should be able to sail fully electric on routes from 50 nm to 100 nm [29].

The FLEXSHIP project involves a consortium of 16 varied partners, each acting as a key stakeholder in the retrofit initiative. Detailed information about these partners can be found in Appendix A. Given the diverse nature of the partnership, each entity must navigate its intrinsic motivations alongside its contributions to the project. On the one hand, they have their usual roles as representatives from a company or organization, and at the same time, they are part of the FLEXSHIP project and will work to achieve the overall project goal.

RV Gunnerus will continue to operate under the Norwegian flag and is classified by the Norwegian Maritime Directorate. When built, the vessel was constructed in compliance with DNV class notations, as detailed in the following table Table 2.4. For the upcoming retrofit process, RINA will be the classification society contributing to and advising on the BESS integration. As the government owns RV Gunnerus, it is not classified by a private classification society, instead, the Norwegian Maritime Directorate conducts inspections and is considered the classification authority.

Table 2.4: Class notation RV Gunnerus [28].

DNV Class	**Notation type**	**Description**
1A1	Main character of class	Hull, machinery, systems, and equipment found to be in compliance with applicable rule requirements
ICE C	Ice class notation	for ships intended for waters with light ice conditions and localized drift ice
E0	Extent of monitoring	Periodically Unattended Machinery Space
R2	Service area notation	Seasonal zones [nm] Winter 50, Summer 100 and Tropical 200

The main stakeholders in the retrofit project are briefly summarized as FLEXSHIP, NTNU, and the vessel's crew. The retrofit was initiated by FLEXSHIP, and without their involvement, RV Gunnerus would most likely not integrate a BESS in the near future. The main source of funding for the retrofit comes from FLEXSHIP, backed by the European Union. However, the final decision on what is to be done on RV Gunnerus should rest with NTNU, the owner of the ship. The crew, although a smaller stakeholder compared to FLEXSHIP and NTNU, holds vital information about the vessel and is potentially the most impacted by the retrofit. A possible divergence in objectives highlights the need for clear and early communication among all stakeholders. For instance, battery placement might lead FLEXSHIP to consider repurposing existing cabins or common areas to enhance performance, potentially at the expense of crew comfort. This underscores the importance of balancing these interests effectively in the retrofit process.

2.4 Motivation for battery integration

A shift towards decarbonization and sustainability is being experienced by the maritime industry, with an increased focus on environmentally friendly solutions, including alternative fuels and various kinds of ESS. Stringent environmental regulations, with which the maritime industry must comply, serve as one of the key motivations for BESS integration. Significant potential for cost savings is also seen with BESS integration, and this importance is amplified with technological advancements within battery technology. The trend has been observed where batteries become more powerful while prices decline. However, the recent trend of a pause in the decline of battery prices, as noted in [34], may suggest challenges in further cost reduction or could be linked to the increasing demand from the industry. For BESS integration to be cost-effective, the installation price must be lower than the expected savings from normal operations within theBESS's lifetime.

The motivation for implementing a battery on RV Gunnerus may differ from that of the majority of the maritime industry, yet the same underlying forces drive it. Making money is the main goal for most of the marine industry; however, there are other reasons for RV Gunnerus. Being financed mainly by the government, for RV Gunnerus, it is important to maintain relevance and cultivate a favorable reputation. Aligning with evolving scientific objectives, thereby contributing to marine research and environmental studies, is also important for the vessels. Installing a battery on RV Gunnerus is a valuable learning process in itself. A BESS installed on the ship will provide new learning opportunities and significantly contribute to the increased knowledge of hybrid propulsion systems. Existing educational experiences and research operations will also be enhanced. For example, the quality of the gathered acoustic data from the sea might be improved when the ship operates fully on electricity, without the noise from a diesel generator.

Implementing a BESS on RV Gunnerus can result in significant operational and fuel savings. Operational savings are achieved through the reduced operational time of the diesel generators, which subsequently decreases the necessity for maintenance. By optimizing the diesel generators' running conditions, fuel efficiency is improved, thereby achieving fuel savings.

Different ways to utilize the battery achieve different desired outcomes. Investigating the possibilities for the BESS to function as a *spinning reserve*, as well as for *strategic loading*, and possibly *Enhanced dynamic performance*, appears most promising for RV Gunnerus. Functioning as a spinning reserve, the BESS enables the vessel to operate with one less diesel generator in some operational modes at certain load ranges, as the battery can supply the necessary power reserve. With the BESS functioning in strategic loading mode, the battery enables the diesel generators to operate in fuel-optimal regions by either charging or discharging when not in an optimal region, concerning specific fuel consumption (SFC).

Enhanced dynamic performance results in more stable running conditions for the diesel generators by letting the battery supply the necessary power in large load steps, and the diesel generator can gradually be increased [35]. This will lead to less wear and tear and lower fuel consumption.

2.5 Risk assessment

Risk is encompassed by the likelihood of an event and the consequences of it. When integrating a BESS onboard a ship, emphasis is placed on identifying the possible hazards that can occur. The severity can be determined by a number of factors such as, injuries, loss of life, environmental impact, downtime, and financial loss. While eliminating all risks is impossible, reducing the risk level to an acceptable level is necessary. Installing a BESS onboard ships is an emerging field, frequently involving unique designs and innovative approaches. Since this technology is still in its infancy, reliability and safety may not yet be fully established. Because of this, obtaining an overview and attempting to detect errors before they occur is paramount. This risk assessment will focus on identifying possible hazards and risk reduction measures. Due to the extent of the thesis and accessibility of relevant information, it will not be a risk matrix concerning statistical probability and consequence of a hazard.

Hazard Identification

Rapid technological advancements highlight the need for safe implementation of the technologies across the sector. Numerous challenges are presented with the integration of a BESS due to the complexity and the fact that it is a relatively new technology undergoing rapid scientific development. For ship operators, lithium-ion batteries currently represent the most popular choice. Besides safety, the main challenges are related to requirements for battery space, weight limitations, and integration with existing systems. The hazard identification (HAZID) process aims to identify and address potential hazards, facilitating better planning and mitigation strategies during the preliminary design phase.

Rapid technological development results in different practices between vendors and approaches to safety and fire extinguishing procedures. Consequently, every system has to be evaluated individually. However, some general factors that should be taken into account are presented in Table 2.5.

Table 2.5: Potential hazards from battery integration, inspired by [36].

Category	Hazard
Electrical	Internal short-circuit External short-circuit Earth faults High impedance Thermal runaway from electric abuse Electromagnetic incompatibility Harmonic distortion Blackout/ dead ship
System/control	Sensor failure Failure of BMS Loss of communication between the battery pack and PMS
Physical	Stability measures Battery space requirements Leakage (electrolyte, cooling system) Mechanical stress Loss of cooling Thermal runaway from mechanical abuse Emission of combustion gases (gas volume, release rate, and gas composition) Overpressure Water event, flooding Fire Rupture of the casing of cell, battery module, pack, or system with exposure of internal components

RV Gunnerus: Hazard identification

An overview of various hazards for the use case RV Gunnerus with regard to the retrofit is presented in the following section. This assessment aims to outline the potential hazards, their causes, effects, and risk reduction measures at this stage. It does not represent an in-depth analysis of the hazards but is meant to give an overview. The followingHAZID is based on the European maritime safety agency (EMSA) guidance on the safety of BESS onboard ships, [36], but is not limited to it.

Table 2.6: HAZID for RV Gunnerus retrofit with BESS.

Hazard type	Cause	Effect	Risk reduction measures
Electrical			
Short circuits	Leakage of cell electrolyte Faulty insulation Faulty wiring Overloading of circuits	Fire, damage to equipment, risk of electrocution and arc-flash	Electrical protection: over current, over voltage Ground fault alarm detection Rapid circuit breakers to prevent electric arc
Electromagnetic incompatibility	Interference with other electronic devices	Component failure	Proper electromagnetic shielding and filtering
Harmonic distortion	Disturbances in the electrical system due to non-linear loads	Disturbance in power supply on component level	Using harmonic filters and designing systems to minimize the effects of non-linear loads
Thermal runaway	Electrical abuse	Gass, smoke, fire and potential explosion	BMS safety features
Blackout condition	Power supply failure	No power supply	Backup batteries for important systems
System/ control			
Sensor failure	Mechanical damage Faulty wiring Loose connection Environmental factors: temperature, sea water	No data from sensor: voltage, ampere, temperature, gas sensor, smoke detection No alarm if outside of normal operating values, potential fire and explosion	Sensor alarm if invalid data Correct IP grading on sensors Redundancies in important sensors
Thermal runaway	Battery ventilation/ cooling system failure	Battery over temperature Gass, smoke, fire and potential explosion	BMS safety feature, redundant wiring for critical functions
Physical			
Improper space	Poor planing	Costly rearrangements	Ensure proper space planning
Fire	Fire inside battery room Fire from external sources	Smoke and toxic gas release, danger to life and material	Plan for fire mitigation strategies Design adequate fire extinguishing systems
Thermal runaway	Mechanical abuse, penetration of battery cell	Gas, smoke, fire, and potential explosion	Structural protection, proper installation, battery room placing
Improper stability	Improper assessment and adjustments during retrofitting	Compromise the ship's stability and safety	Ensure a good trim evaluation process during design
Improper trim	Improper assessment and adjustments during retrofitting	Compromise the ship's stability and propulsion efficiency	Ensure a good trim evaluation process during design

From this HAZID, the relevant hazards for this thesis are further investigated. Thermal runaway is evaluated to be the biggest hazard, due to the dangerous effects regarding safety. How to prevent thermal runaway will be further investigated in subsection 4.3. Hydrostatic evaluation and space planning are elaborated in subsection 4.2 and subsection 4.4. Power quality, where harmonic distortion is elaborated, can be found in subsection 5.2. Electric protection and selection are reviewed in subsection 5.4.

3 Concept design

Following the pre-conceptual analysis of the project, with an understanding of the desired outcomes and constraints, the project enters the concept design phase, where the potential of a BESS integration will be evaluated from a technical perspective. Initially, the placement options for the battery space will be evaluated through a space analysis. Following this, a preliminary sizing strategy for the integration is presented as a starting point. The sizing strategy evaluates the required energy and power demand, and together with the state of charge (SOC) window, different electrical sizes are proposed. With the suggested battery sizes, the potential fuel savings are calculated based on the operational modes with their load profiles. The battery chemistry is also evaluated in general, for RV Gunnerus. Finally, potential general grid architectures for the use case are presented and evaluated.

3.1 Space analysis

The retrofitting of a vessel with a BESS is a complex process, encompassing several considerations related to available space. Because the ship is already built, it is vital to identify the existing limitations related to the battery placement and the integration of sub-systems such as cooling, ventilation, and fire systems. A preliminary analysis of the available space onboard is necessary.

For RV Gunnerus, assessing different battery locations begins with examining available onboard spaces. These areas are then evaluated for their compatibility with installing thermal management systems, ventilation, and fire protection measures. Accessibility and proximity to the existing power grid also require evaluation. The industry offers a variety of installation packages, ranging from modular cabinets that represent flexibility to container solutions suitable for placement on the ship's deck, which represents easy integration.

Space on RV Gunnerus is a limiting factor. With no available free spaces suitable for easy conversion into battery compartments, careful consideration is needed to determine the optimal battery placement and additional electrical cabinets. Furthermore, two permanent magnet Azimuth thrusters were mounted from the former Rolls-Royce Commercial Marine in 2015, and its midship section was extended by 5 meters in the spring of 2019. As a result of this process, the ship is currently aft-heavy, with the bow already fitted with 10 tonnes of fixed ballast and always operating with the forward ballast tank full. This emphasizes that the longship trim should also be considered when evaluating potential battery spaces.

At this stage in the process, the following alternatives for battery placement are considered feasible for RV Gunnerus:

- Aft cargo hold: The aft cargo hold is the biggest currently available space. However, it might pose some challenges as the ship is already aft heavy.
- Engine room: An alternative involves removing one engine to make space for a battery. This option is considered positive due to replacing heavy machinery with a battery and the short distance to the existing power grid. However, challenges may arise regarding fire safety and trim, as the batteries, potentially heavier than the engine and placed in the aft part of the ship, could affect the ship's longship trim.
- Dry provision: Another option would be to retrofit the dry provision room. This room is about $6m^2$. However, it may pose some challenges, such as the area being far from the existing power grid and insufficient size.

- Living quarter 1. Deck: Optionally rebuilding the existing forward living quarter to a battery space could be an option. The stakeholders have to evaluate this concerning the loss of valuable accommodation.

- Container on deck: From a physical integration perspective, the simplest solution would be to place a complete battery container system on the ship's deck. This would allow the battery with subsystems to function separately from the onboard systems. However, the downside of this solution is that it would compromise the function of using the deck for research purposes.

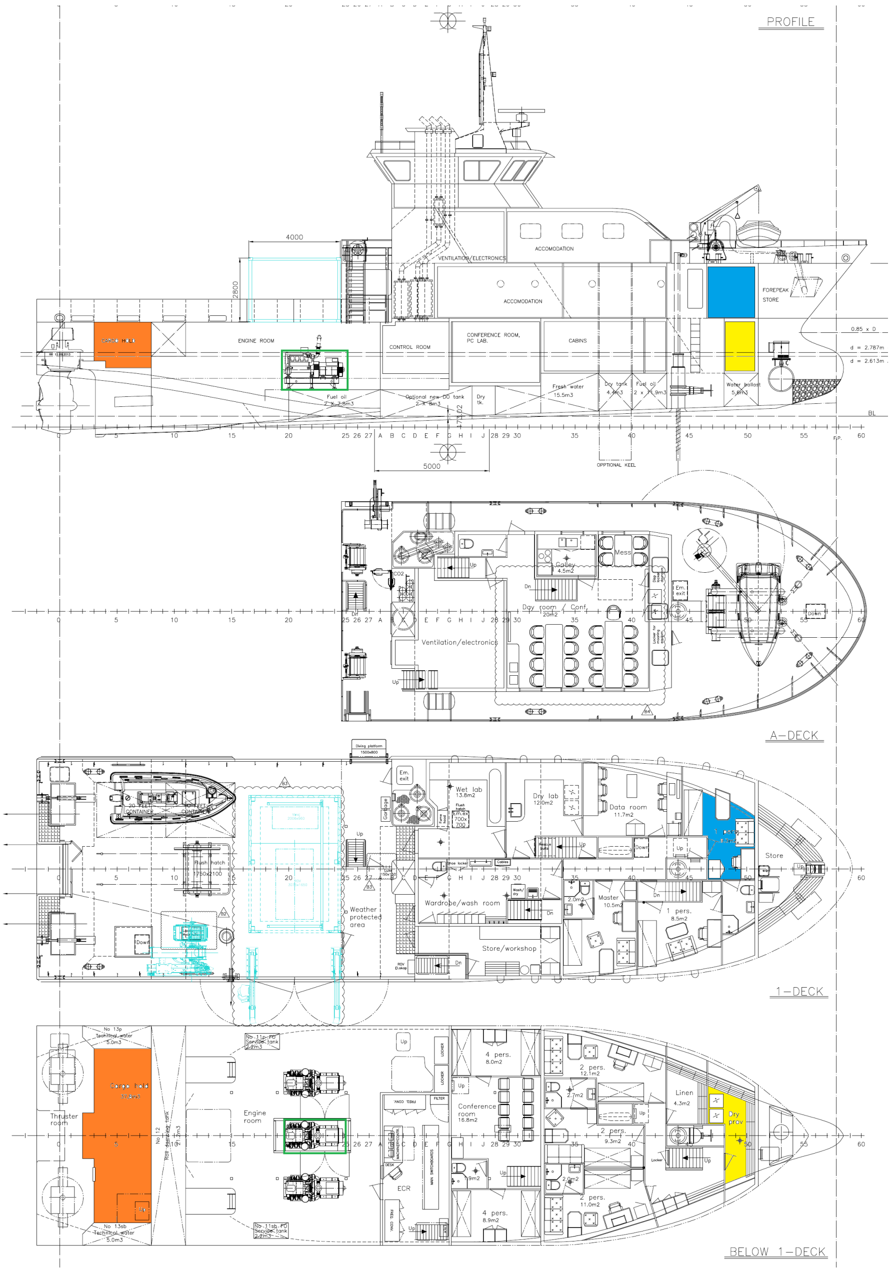


Figure 3.1: Technical drawing of RV Gunnerus with alternatives for battery space.

These spaces need to be assessed in terms of their suitability for installing thermal management systems, ventilation, and fire protection. Maintenance accessibility and proximity to the existing power grid must also be evaluated. A more detailed evaluation will be conducted in the preliminary design phase based on the requirements of the necessary battery size in section 4.2.1.

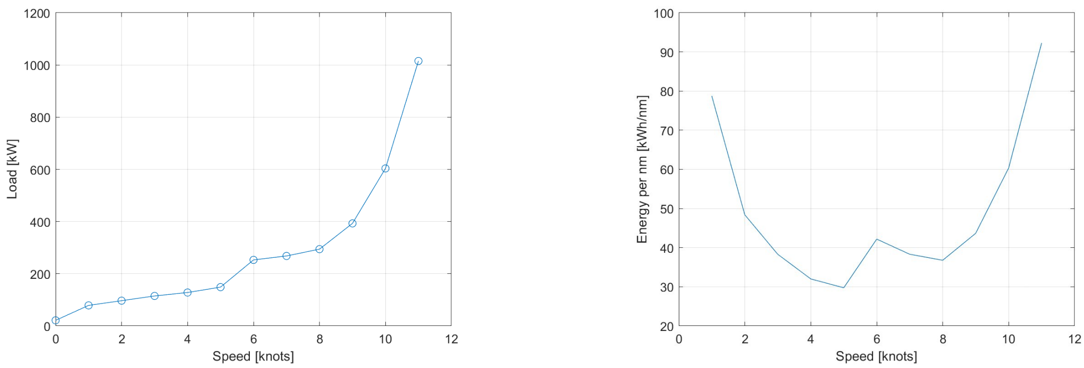
3.2 Sizing and selecting

In this concept design phase, the sizing foundation is set by analyzing the operational modes and different battery utilizations. Three modes will be investigated to evaluate the necessary battery size: fully electric, spinning reserve, and strategic loading. An extended analysis of load profiles has been conducted to accurately determine the power requirements for battery use. For the sizing, ideal conditions are assumed, implying no losses to converters, the battery, or other system components. However, the output power from the generator is evaluated, i.e., engine and generator losses are accounted for. When the necessary available energy is determined, an evaluation of battery degradation and SOC window is reviewed, and finally, a selection of battery size and rates are presented.

Sizing

Fully electric

FLEXSHIP aims for RV Gunnerus to achieve a range of 50-100 nautical miles on electric power alone. A curve illustrating the relationship between vessel speed and load demand is presented in Figure 3.2a. This graph is based on the results from a sea trial test conducted on October 25, 2023. The figure is derived from the power output of the generators at various vessel speeds, incorporating the typical auxiliary demand associated with the vessel's operations. Table 2.3 shows that RV Gunnerus transits with an average demand of 670 kW, corresponding to 10.15 knots. The values are replotted to identify the most power-efficient speed, showing the necessary energy per nautical mile in relation to vessel speed. Figure 3.2b demonstrates that 10.15 knots is not the most efficient speed in terms of power demand. Sailing at 5 knots would enable the Gunnerus to achieve a longer range. Table 3.1 shows the required battery power at the current cruising speed for both 50 nm and 100 nm ranges.



(a) Load demands for different speeds. (b) Energy demand per nm.

Figure 3.2: Power requirements for vessel speed RV Gunnerus.

Spinning reserve

The spinning reserve refers to the battery functioning as a standby power source. Although connected to the power grid, the battery does not discharge or charge under ideal conditions. Upon generator failure, the battery instantly provides the necessary power. Currently, a running generator fulfills the spinning reserve requirement for DP operations, although the average power demand is only 90 kW, as illustrated in Table 2.3. For the battery to function as a spinning reserve across the generator's entire operational range today, it must be able to discharge 450 kW. In the worst-case scenario, the battery must sustain this power until a new generator can supply the required power. The crew indicates that starting a new generator typically takes about 10 seconds, however, a certain safety margin must be accounted for. Conversations with the crew suggest that a battery capable of supplying sufficient power for 10 minutes is deemed adequate. The required battery energy is calculated in Equation 1. In Table 3.1, the required size of the battery for spinning reserve is presented.

$$Required\ energy = Discharge\ power \cdot Time = 75kWh \tag{1}$$

Strategic loading

In strategic loading usage, the diesel generators operate under close to ideal conditions, with the battery managing any deviations from these conditions. Two diesel generators are running for redundancy during harbor maneuvering and DP operations. The demand is often low in these operating modes, and it is reasonable to charge the battery. It is not a question of whether to start or stop a diesel generator and to charge or discharge the battery. This makes strategic loading a viable alternative mostly for transit mode. However, the diesel generators are close to optimal conditions in transit mode with optimal speed. This makes strategic loading most interesting when transiting at suboptimal speeds.

During standard transit operations, two generators are running to achieve a combined output power of 675 kW, as detailed in Figure 3.5b. Deviations from this 675 kW output can be managed by supplying or consuming energy through the battery. Over a 10-hour period, this dynamic is illustrated in Figure 3.4a, showing the cumulative sum of energy supplied to and consumed by the battery within a load profile. Using a stochastic approach, this profile is generated based on the histogram for power demand during transit, as shown in Figure 2.6. The compact nature of the histogram suggests minimal fluctuations in the generated load profiles, leading to a comparatively low energy demand on the battery. It is important to note that this method is sensitive to load variations, and if it was based on transit data with more speed variations and not as close to optimal transit speed, it would likely yield a different result. The graph indicates that the required energy available for strategic loading in transit is approximately 1 kWh.

As strategic loading with two generators requires 1 kWh, exploring the potential for using one generator alongside the battery in transit mode becomes interesting. Although this operational mode is not sustainable for a long transit, a typical voyage based on AIS data is evaluated.

This approach is predicated on the usual transit being relatively short and the assumption of departing the harbor with a fully charged battery. The operation would involve departing with one running generator and a discharging battery, then transiting to the area for DP operation. By enabling the generator to recharge the battery during DP operations, the grid can discharge the battery during transit back to the harbor. In Figure 3.3, a circle is drawn out from the home harbor in Trondheim, with a radius of 15 nm. The time spent inside this circle, but outside the harbor box, is 498 hours in 2023. This represents 45% of the time at sea. An estimation can then be made that RV Gunnerus may utilize transiting with one generator and a battery instead of two generators for 45% of the time at sea.

A 15 nm distance represents 1.5 hours of transit at 10 knots, and the total energy supplied by the battery is calculated to be 508 kWh, as depicted in Figure 3.4b. The necessary battery size to meet this energy requirement is outlined in Table 3.1.

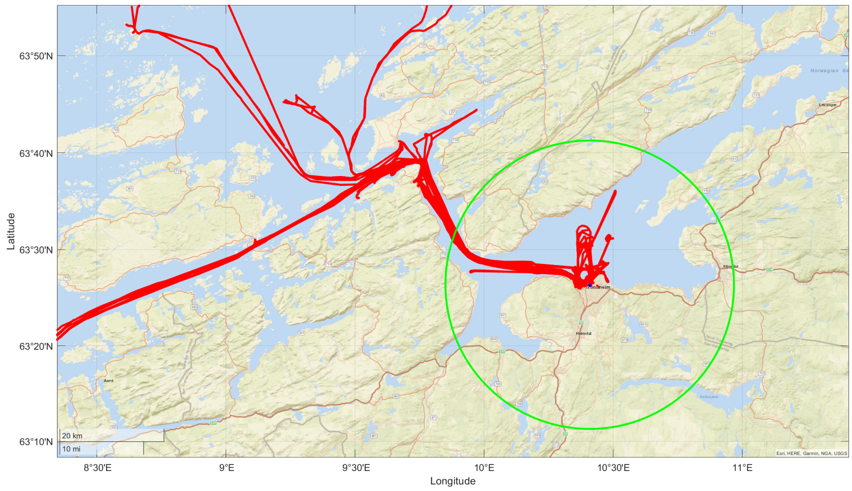
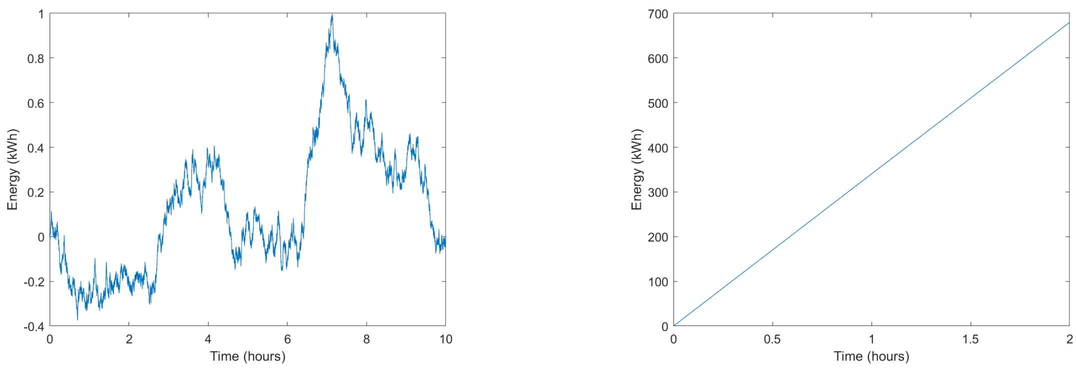


Figure 3.3: 15 nm radius circle from Trondheim harbor.



(a) Required energy with two generators, 10 hours.

(b) Required energy with one generator, 2 hours.

Figure 3.4: Energy (dis)charged from battery in transit.

As illustrated in Table 3.1, the battery size ranges from 75 kWh to 11000 kWh, depending on how to utilize the battery. Choosing the largest battery offers the most significant flexibility but incurs higher costs and requires more space. The information in the table should be assessed in conjunction with the stakeholders' intentions, desired outcomes, and operational modes. When not at berth, RV Gunnerus primarily conducts DP operations, indicating that the most significant benefits of the battery are achieved during DP operations. Given the low demand while two generators are operational, utilizing the battery as a spinning reserve is highly advantageous. FLEXSHIP, a key stakeholder, aims for a 50-100 nm range on fully electric power. As the table indicates, achieving this range requires a significantly larger battery than needed for spinning reserve usage.

Table 3.1: Battery size.

Battery usage	**Fully electric**				**Spinning reserve**	**strategic loading**
	50 nm		100 nm			(1gen, 15nm)
	5 kts	10.15 kts	5 kts	10.15 kts		
100%	1487 kWh	3300 kWh	2975 kWh	6600 kWh	75 kWh	508 kWh
80%	1859 kWh	4125 kWh	3718 kWh	8250 kWh	94 kWh	635 kWh
60%	2479 kWh	5500 kWh	4958 kWh	11000 kWh	125 kWh	847 kWh

Meeting the FLEXSHIP goal of operating fully electric on routs of 50 nm requires 1487 kWh of available energy. Given the significant difference a fully electric voyage presents from normal operations, further study is given to a typical research voyage of RV Gunnerus.

An initial energy requirement can be estimated based on the typical voyage of 15 nm to DP operation, transiting with one generator and a discharging battery. Assuming that RV Gunnerus starts with fully charged batteries, charged with green energy from shore, it can complete its 15 nm transit, which requires 508 kWh. Once RV Gunnerus arrives at the DP operation area, at least 75 kWh remaining available energy must be available. Once conducting the DP operations, it can start to charge the battery and prepare the transit back to the harbor. The required energy for such a scenario is shown in Equation 2.

$$\begin{gathered} Required\ energy = (transit\ requirement\ +\ Spinning\ reserve\ requirement) \\ Battery\ size = (508 + 75) = 582kWh \end{gathered} \tag{2}$$

Battery degradation

Once the required energy is stated, the SOC window determines the actual electrical size of the battery. Batteries usually degrade excessively when operated in the ends, i.e., near 0% and near 100%. Chowdhury et al. [37] studied the battery degradation and aging in batteries operating in 10% SOC windows from 0% to 100%. The best performance was when the batteries were cycled between 30%-55%. However, in hybrid vessels, this would require a relatively large battery. To extend this window, they concluded using higher SOC was better. Especially SOC ranging from 5% to 15% lead to rapid aging. Gao et al. [38] concluded that for 20%-40%, 40%-60%, and 60%-80%, the aging mechanisms were similar, however for 0%-20% and 80%-100%, the degradation was quicker. Both studies imply that 20%-80% cycling is a good balance between preserving and utilizing the battery.

The exact optimal SOC window is also influenced by the type of lithium battery and is ultimately defined by the battery manufacturer. It depends on factors such as the amount of energy throughput, number of cycles, available space, battery type, and power rates. For instance, utilizing 100% of the battery would necessitate more frequent replacements. Conversely, using only 25% of the battery would require more space but would prolong the battery's lifespan. For further estimation and calculations, a 60% battery utilization is considered. Accounting for the SOC window results in larger batteries than those required for available energy. The battery size for a 50 nm fully electric transit and the described DP scenario are given in Equation 3 and Equation 4, respectively.

$$Battery\ size = Required\ energy \ \cdot \ SOC\ Window$$

$$Battery\ size_{50nm,electric} = 1487 \cdot \frac{1}{0.6} = 2478\ kWh \tag{3}$$

$$Battery\ size_{DPscenario} = 582 \cdot \frac{1}{0.6} = 970\ kWh \tag{4}$$

Selecting

Additionally, an adequate e-rate is necessary to achieve a fully charged battery by the end of the DP operation and to provide sufficient power during transit. The e-rate, defined as the maximum power in watts at which the battery can charge and discharge divided by its capacity, may vary between charging and discharging. Given the battery's voltage variation with the SOC, calculating the c-rate in amperes would be more precise. However, due to unknown voltage at this project stage, the e-rate is utilized instead. Upon completing 100 hours of a randomly generated transit, the highest recorded peak demand reached 770 kW. Given a generator's ideal output of 335 kW, the battery must supply an additional 435 kW to meet peak demand, setting the minimum discharge e-rate. In scenarios where DP operations require no power, and the generator supplies 335 kW under ideal conditions, the battery must be able to charge at 335 kW to maintain those conditions. For simplicity, a uniform 435 kW is applied for both charging and discharging. The formula to calculate e-rate is shown in Equation 5. Concerning this scenario, the 940 kWh battery would need an e-rate equal to 0.45, and the 2468 kWh battery would need an e-rate equal to 0.18.

$$e - rate = Power\ [kW]\ /\ Capacity\ [kWh] \tag{5}$$

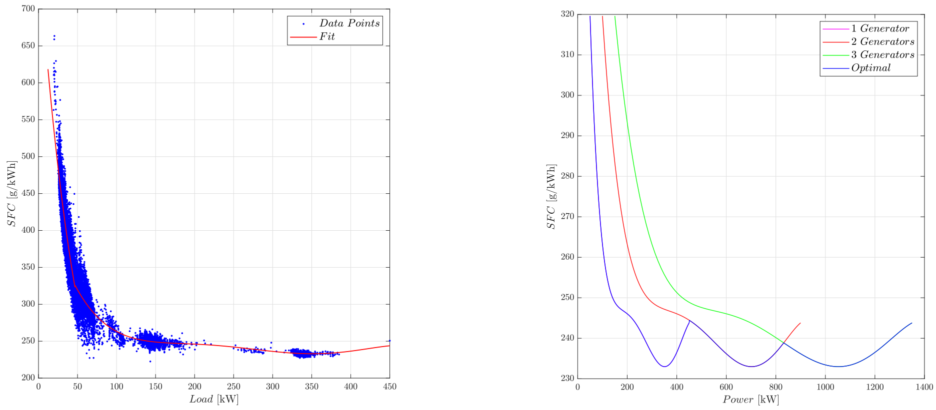
By studying the load demand for different speeds, Figure 3.2a, running fully electric may demand up to 1025 kW, which requires an e-rate of 0.41 for the 2478 kWh battery. Similarly, to run fully electric with the 970 kWh battery will require an e-rate of 1.06.

The following section calculates potential fuel savings with battery integration using two sizes: one at 2500 kWh with an e-rate of 0.5 and one with 1000 kWh capacity with an e-rate of 1.1.

3.3 Potential fuel savings with battery

In this section, an estimation of possible savings of retrofitting RV Gunnerus with a battery is conducted. The savings are quantified in terms of fuel savings. Today's fuel consumption is compared to the optimal usage of today's system without a BESS integrated and the optimal usage with a BESS integrated. A retrofitting design is an iteration design process, and all analyses and calculations are based on the current information. They may later be updated as new information and data arrive.

The method for evaluating the possible savings is based on Mo and Guidi's method, proposed in [39], and is based on considering steady-state at each load demand. The first objective is to establish a model to illustrate the present fuel consumption for RV Gunnerus. Data regarding fuel consumption [L/h] and load demand [kW] were sampled. Based on this data, SFC data can be plotted, the blue dots in Figure 3.5a. Note that the load on the x-axis is output power from the generator, i.e., internal losses in both the diesel engine and the generator are accounted for. The SFC curve, the red line, is calculated with linear interpolation between the samples, which varies around 1 Hz. The load and fuel consumption data are then balanced with linear interpolation over the time data. The results are then filtered with an upper and lower band for y values, and results outside two times the standard deviation are excluded. A piecewise curve fitting strategy was chosen to best fit a curve over the plotted results. There was no data on power generation over 380 kW, so an estimation of full-load fuel consumption was made. The factor between the measured SFC and the gross power SFC at 3/4 load, Appendix B, was multiplied with the gross power SFC at full load, for an estimation on the full load SFC from output power.



(a) SFC curve fitting.

(b) SFC for 1-3 diesel generators without battery.

Figure 3.5: SFC curves for RV Gunnerus.

Based on the fitted curve, three curves for 1-3 generators are drawn out in Figure 3.5b. The blue line indicates the optimal load shearing for minimizing the SFC. This figure represents a case with no battery and no requirements for spinning reserve. By evaluating the load profiles defined in subsection 2.2 and Figure 3.5b, the fuel consumption for each mode can be calculated for today's operation, optimal operation without battery, and finding the theoretical best consumption with a battery installed.

For calculating the current fuel consumption, the load profiles are calculated with the number of generators presented in Table 2.3 and the fuel consumption curve in Figure 3.5b, for the given amount of generators. The current way of operating RV Gunnerus is not optimal when in DP operations and harbor maneuvering, due to the redundancy requirements. As the demand is low, yet two diesel generators are running, the fuel consumption is relatively high. When calculating the optimal operation without the battery, the load is always supplied with the optimal number of generators, following the blue line in Figure 3.5b. There is no requirement for a spinning reserve or penalty for starting and stopping a generator. The results are presented in Table 3.2.

To understand the potential of battery integration, the theoretical minimum fuel consumption with battery integration is investigated. This is estimated by assuming that the generators always operate at their lowest SFC. This estimation represents the theoretical lowest fuel consumption achievable when integrating a battery. Note that this does not take shore charging into account.

Comparing the three values illustrates the potential savings and highlights how much can be achieved without any integration at all. These comparisons provide a clear picture of the potential fuel savings and operational improvements achievable through battery integration.

Table 3.2: Fuel consumption without battery.

	Today's redundancy	**Optimal without battery**	**Theoretical minimum**
Harbor maneuvering	31.04 kg/h	24.11 kg/h	17.25 kg/h
Transit	156.43 kg/h	156.43 kg/h	130.69 kg/h
DP	33.57 kg/h	26.26 kg/h	18.79 kg/h

Next is to consider RV Gunnerus' fuel consumption with a battery. The two battery sizes that will be considered are 1 MWh and 2.5 MWh, regarding the three operational modes. The strategy for calculating savings is based on an offline, steady-state method [39]. Furthermore, shore charging is not considered, meaning that the generators produce all power. The strategy is based on letting the generators run at their ideal load in every load demand; if the load demand is not close to the ideal, the battery is either charging, or one generator is shut down, and the battery is discharging. Theoretically, the battery would always charge or discharge if the demand is one kW more or less than the optimal load. However, due to losses when charging and discharging, the generators power the grid without the battery when operating near the ideal loads. Charging and discharging losses are expressed in Equation 6 and Equation 7, respectively. As the strategy switches between charging and discharging, the battery size explicitly only affects the number of cycles. Mo and Guidi illustrate how the cycles can be implemented with minimum savings per cycle [39]. However, this factor is acknowledged but not quantified when estimating fuel savings for this concept design. Due to the $P_{B,max}$ term, the losses due to charging and discharging are slightly influenced by the battery size, however, the difference is negligible.

$$P_{l,C} = p_{l,0} \cdot P_{B,Cmax} + p_{l,C} \cdot P_{B,C} \tag{6}$$

$$P_{l,D} = p_{l,0} \cdot P_{B,Dmax} + p_{l,D} \cdot P_{B,D} \tag{7}$$

The system data for coefficients and battery properties are presented in Table 3.3. With the SFC curves and the loss equations, optimal usage of the battery can be calculated following Equation 8.

$$SFC_{DG,opt}(P_L) = min\{SFC_{DG}(P_L, P_{B,C}, P_{DG,C})\} \tag{8}$$

The decision variable is Equation 8 is the charging power ($P_{B,C}$), and it must be decided over the total load range (P_L). To do so, a Matlab script tests every charging power ranging from 0 kW to 1025 kW. The generator power is calculated for every scenario as shown in Equation 9.

$$P_{DG,C} = P_L + P_{B,C} + P_{l,C} \tag{9}$$

With this power from the generators, the SFC is calculated following Equation 10. The script then stores the best charging power for the given load.

$$SFC_{DG} = \frac{SFC_{no.bat} \cdot P_{DG,C}}{P_L + P_{B,C}} \tag{10}$$

The SFC curves for RV Gunnerus with a battery are illustrated in Figure 3.6. The curves represent the operational mode with no requirement for spinning reserve.

Table 3.3: System data.

Storage energy	E	1000 kWh	2500 kWh
Storage maximum charge and discharge power	$P_{B,Cmax}$, $P_{B,Dmax}$	1100 kW	1250 kW
Storage and converter charge loss coefficient	$p_{l,C}$	0.04	0.04
Storage and converter discharge loss coefficient	$p_{l,D}$	0.04	0.04
Storage and converter constant loss coefficient	$p_{l,0}$	0.001	0.001

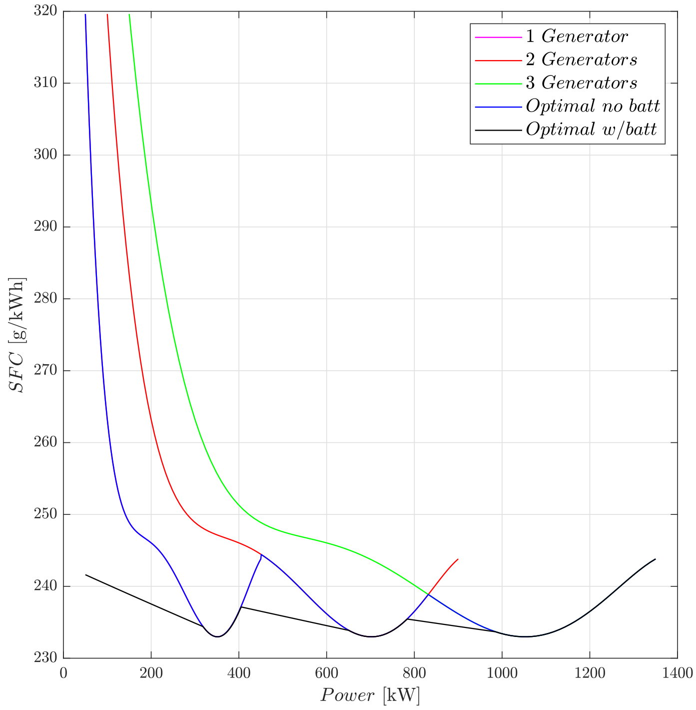
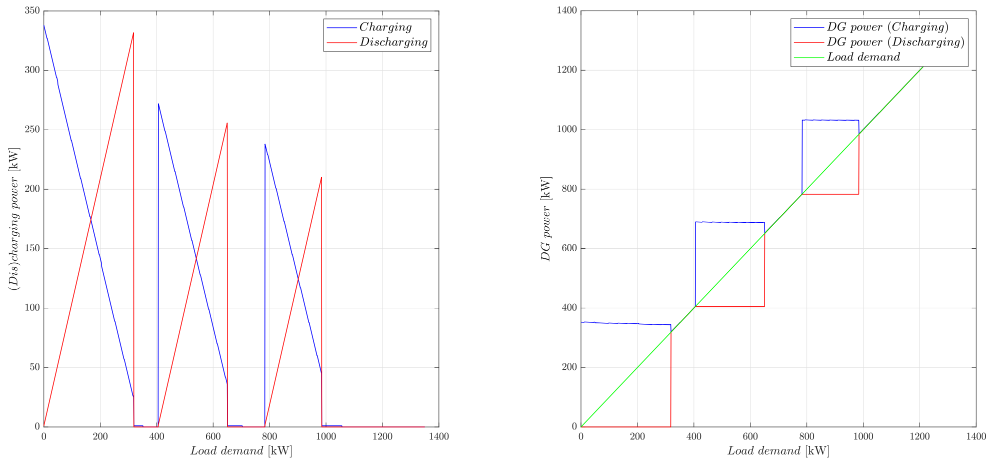


Figure 3.6: SFC curves for RV Gunnerus with battery.

Since the strategy is considering a steady state, the discharging has to happen in the same load demand areas as charging. The optimal charging and discharging power under different load demands are presented in Figure 3.7a, and the optimal generator load during charging and discharging are presented in Figure 3.7b. This is for the case with no spinning reserve or shore charging requirements.



(a) Optimal charging and discharging power.

(b) Optimal DG load.

Figure 3.7: Usage of battery and generators.

By establishing SFC curves for optimal usage of the battery, one can estimate the fuel consumption for RV Gunnerus with a battery under the same condition as presented in Table 3.2. The results are presented in Table 3.4. The "Today's redundancy" column represents the case where the battery is used as a spinning reserve. There is no power flow through the battery, it only works as a redundancy, together with one running engine. However, the "optimal with battery" case RV Gunnerus can run purely on battery in the situations illustrated in Figure 3.7b. In transit mode, RV Gunnerus is running outside the areas where the battery is utilized, so there will be no savings with a battery for this case.

Table 3.4: Fuel consumption with battery.

	Today's redundancy with battery	**Optimal with battery**
Harbour maneuvering	24.11 kg/h	21.24 kg/h
Transit	156.43 kg/h	156.43 kg/h
DP	26.26 kg/h	20.84 kg/h

A comparison of fuel consumption for the operational modes and a complete voyage based on the relative time at sea, as illustrated in Table 2.3, is presented in Table 3.5. Today's redundancy without battery represents today's fuel consumption and is presented as 100%. This value is compared to today's redundancy with battery, optimal operation with and without battery, and the theoretical minimum fuel consumption. Note that this is calculated without the opportunity of shore charging. Furthermore, the calculations are done based on load profiles, and integrating a battery presents great flexibility in areas other than what the load profiles represent; this effect is not visualized in the table. The fuel consumption illustrated in Table 3.5 represents both the 1000 kWh battery and the 2500 kWh battery, i.e., there is no difference in fuel savings. This argues for choosing the smaller battery, however, the smaller battery will not cope with FLEXSHIP's goal of sailing 50 nm fully electric. When physical space and weight are evaluated, the choice between the batteries will be made in the next iteration.

Table 3.5: Comparison of fuel consumption.

	Harbor maneuvering	**Transit**	**DP**	**Voyage**
Theoretical minimum	55.5 %	83.5 %	56 %	63.8 %
Optimal with battery	68.4 %	100%	62.1 %	73.4 %
Optimal without battery	77.7%	100 %	78.2 %	84.3 %
Today's redundancy with battery	77.7%	100 %	78.2 %	84.3 %
Today's redundancy without battery	100 %	100 %	100 %	100 %

3.4 Battery type evaluation

When integrating a BESS onboard vessel, one of the key components is the actual battery. At this stage, the different chemistry technologies for batteries will be evaluated. The key battery technologies that can be used for fleet electrification/hybridization depend on the given battery chemistry, with a wide range of products existing representing different levels of quality and performance. Not all batteries are created equal, even batteries of the same chemistry include trade-offs involving power, energy, and durability [40].

A lithium-ion battery is assembled by connecting basic lithium-ion cells in parallel and/or series to achieve the desired voltage and current. Several battery cells can be combined to form a module, and multiple modules can be integrated into a battery pack. Typically, a basic lithium-ion cell consists of a cathode (positive electrode) and an anode (negative electrode), both immersed in an electrolyte containing lithium ions. The electrodes are separated by a typically microporous polymer membrane known as a separator. This separator permits the exchange of lithium ions between the electrodes while preventing the movement of electrons [41].

From the perspective of integrating a battery pack onboard a vessel, certain factors gain importance. First, the energy density, both volumetric and gravimetric, is essential as it determines the efficiency with which the type of battery can utilize the available space and meet weight requirements. The charge and discharge C-rates are important in evaluating the battery's capacity to deliver power and the speed at which it can be recharged. These rates must be compatible with the vessel's power consumption and the power surplus for charging.

The most common lithium-ion battery chemistries used onboard vessels today are NMC, LFP, and LTO, [42]. However, despite having the same basic chemistry, their specifications may vary depending on producers and system design. High-power batteries quickly deliver large amounts of power, which is ideal for applications that need quick energy bursts, like engine startups. On the other hand, high-energy batteries are made for prolonged energy release, making them suitable for electric vehicles and portable electronics that require long-lasting power. Different lithium-ion batteries will be further evaluated regarding the possibility of implementation.

With nickel manganese cobalt (NMC) batteries, the name refers to the cathode material used, $LiNi_{1-x-y}Mn_xCo_yO2$, traditionally it is paired with graphite on the anode side. The strength of this combination lies in the attributes of its constituent elements, nickel, which offers high specific energy, cobalt, also known for its high specific energy, and manganese, doped into the layered structure for stabilization. By adjusting the relative composition of these elements, it is possible to alter properties related to power density, energy density, cost, and safety. This allows for tailoring the cells to meet the demands of specific applications or groups of applications [43].

With lithium iron phosphate (LFP) batteries, the name also refers to the cathode material used, $LiFePO_4$, which also traditionally pairs with graphite on the anode side. Unlike NMC with its layered metal oxide structure, LFP features a phosphorous-olivine structure. This structural difference results in a lower risk of thermal runaway for LFP, as it lacks oxygen in its composition, thereby enhancing resilience to temperature fluctuations. However, this also leads to LFP having lower specific energy and voltage compared to NMC, which in turn reduces the cell's driving force [43].

With lithium titante oxide (LTO) batteries, the name refers to the anode material used, $Li_4Ti_5O_12$, instead of the normally used graphite, and it can be paired with different cathode materials. Lithium titanate, known as a zero-strain material, has a spinel structure, which undergoes negligible volume change (less than 1%) during lithium-ion insertion and extraction. This attribute offers excellent cycling stability, with the potential for over 20 000 cycles, but the energy density is lower. Lithium titanate batteries do not have solid electrolyte interphase, which helps avoid capacity fade, thereby contributing to a longer lifespan [44].

A brief overview of the specific energy for the most typical lithium-ion batteries in ships today is provided in Table 3.6. This table is derived from a study of 30 ships equipped with a BESS today, as reported in [42]. This study evaluated 30 ships equipped with a BESS. NMC batteries constitute the largest segment of the market, being utilized in 20 out of the 30 systems, while LFP batteries are used in 8 of them. LTO batteries are used in only 2 systems within this analysis. Average specific energy and average energy density are determined based on cell chemistry, cell shape, and system design. They are calculated solely for the battery system, not accounting for the required service space or battery room height.

Table 3.6: Energy density per cell chemistry, [42].

Battery type	**Gravimetric energy density [Wh/kg] range/average**	**Volumetric energy density [Wh/L] range/average**
LFP	50-120 / 81	25-140 / 79
NMC	75-180 / 107	50-260 / 116
LTO	60-80 / 67	50-100 / 76

Regarding average energy per cell chemistry, it is observed that NMC cells yield a higher volumetric and gravimetric energy density. Although LTO has a relatively low energy density, it can be considerably affected by the system's design, and the Seabat analysis only includes two LTO batteries. It is noted that several of the LFP batteries in the study performed similarly to the majority of NMC batteries with regards to energy density. However, a couple of the LFP ones performed significantly low and some of the NMC performed exceptionally high, [42]. This significant difference in some batteries can be due to the SOC window usage and the cells' shape. To compare with data from the electric vehicle industry, Liu et al. [45] summarize with the following table regarding key properties and costs:

Table 3.7: Comparison of battery types.

Battery type	**Energy density**	**Life span**	**Cost**
NMC	High	High	High
LFP	Low	High	Low
LTO	Very low	Very high	Very high

Use case results: Battery type

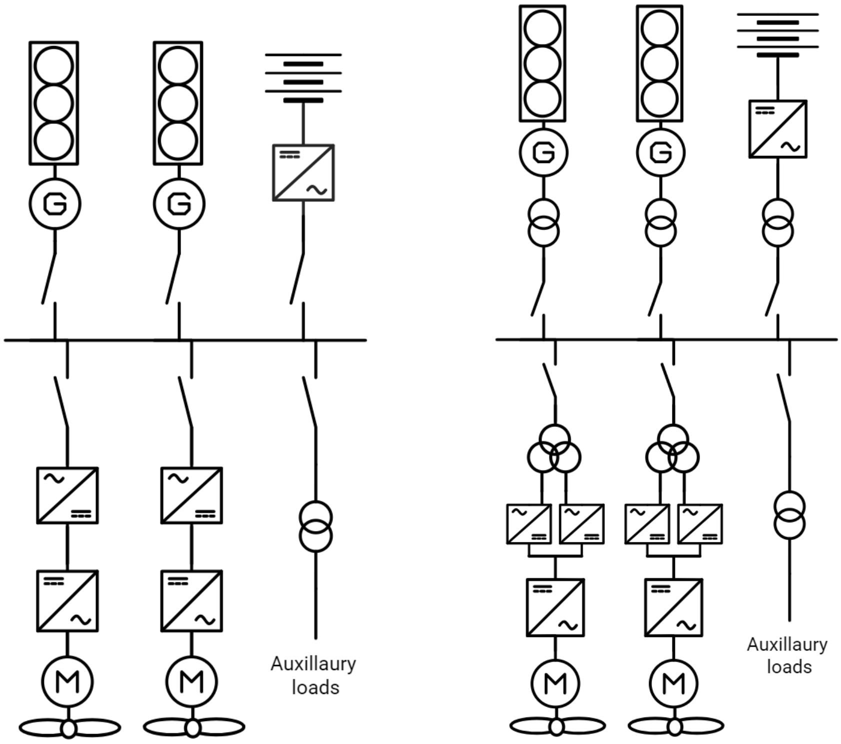
Every vessel retrofit will have unique battery installation requirements. Consequently, the overall FLEXSHIP goal of developing a safe and reliable, flexible, modular, and scalable solution is difficult. Different vessels pose different challenges. In the use case of RV Gunnerus, the utility of available battery space with flexible vessel integration is essential, given its limited space.

Upon evaluating the existing solutions, NMC battery technology is recommended as it is currently the most widely adopted. It has been demonstrated to be adaptable regarding power density, energy density, and safety. It can be expensive, but it has proven to have the highest energy density, which will be essential to achieving the FLEXSHIP goal.

3.5 Power distribution: Grid topology possibilities

An efficient, safe, and reliable power distribution system is essential in marine vessels, regardless of whether it is a shipping or fishing vessel. The electrical grid topology is the blueprint for the onboard electrical power distribution, directly influencing operational efficiency and system reliability. When retrofitting a vessel with a BESS, there are several important factors to consider and possibilities concerning the ship's electrical grid. The existing electrical grid will set some boundaries, making a completely new power distribution system difficult. One must consider both the feasibility of installing the new components and laying new cables, as well as the cost aspect of the retrofit. Other important factors to consider when constructing an electrical grid are operating voltage and power, energy efficiency, integration complexity, cost, size, and weight. This section discusses some initial general alternatives for electrical grid solutions and their strengths and weaknesses. It is an iterating process where the most promising solutions will be further investigated and specified in section 5, regarding the existing electrical grid onboard RV Gunnerus.

This section investigates five different electrical grid possibilities with the integration of a BESS. Two AC grid SLDs are shown in, Figure 3.8a and Figure 3.8b, a hybrid grid SLD in Figure 3.9, and two DC grid SLDs in, Figure 3.10a and Figure 3.10b. While these figures are simplified and do not show all the details, they represent general solutions applicable to various electrical grid topologies.



(a) AC grid 1, low voltage (LV). (b) AC grid 2, medium voltage (MV).

Figure 3.8: AC grid 1 and AC grid 2.

In Figure 3.8a, there is a SLD with a LV configuration. The power sources and the propulsion are connected through the AC main switchboard with the help of power converters or power conditioning stages. The auxiliary load, or the hotel load, is fed through a transformer serving as galvanic isolation between the loads and the main switchboard, as well as the possibility for voltage adjustment. The propulsion system is connected to the main switchboard through an AC-AC converter. Its purpose is to rectify the current to DC and then invert it to the desired AC output in terms of both magnitude and frequency. The battery is connected to the main switchboard through an active front end (AFE) AC-DC converter. The AFE AC-DC converter is bidirectional, enabling the battery to supply and store energy, i.e., discharging and charging. The EMS sends desired values to the BESS through the BMS and the AFE, and it is the AFE that ultimately regulates the battery usage. The EMS decides how to utilize the battery, such as peak shaving and load leveling, but the AFE executes the operation. The configuration and interaction between these components are vital for a stable and functional system.

Figure 3.8b presents a SLD of a MV configuration. The MV distribution system has proven to be a good solution for larger vessels, for example, large cruise ships [46]. The diagram is based on the same system as the LV configuration in Figure 3.8a, but there are some important differences. It is necessary to include a step-up transformer from the power supply to the main switchboard and a step-down transformer from the main switchboard to the propulsion and auxiliary loads. Depending on system requirements, the propulsion load transformer can also be a two-winding transformer or completely removed from the system. Utilizing higher voltage levels offers multiple benefits, particularly under conditions of high power demand, primarily due to the lower currents in the power system. This reduces currents for various system components, including MV switchboard breakers, power converters, cables, and propulsion motors. The decrease in current is in proportionate to the increase in operating voltage. Consequently, this leads to a decrease in the overall size, weight, and cost of the system, as well as reduced energy losses in applications that require higher power. However, the need for large transformers adversely affects the power system's size, weight, cost, and energy efficiency, marginally diminishing the advantages of MV integration compared to its LV counterpart [46].

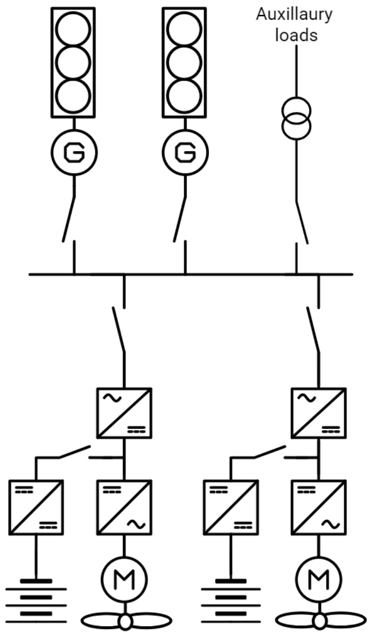
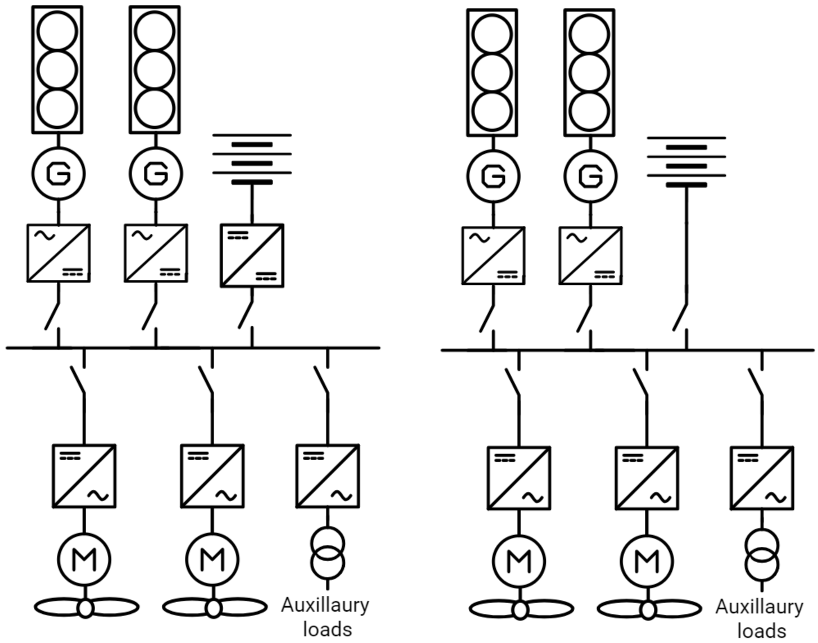


Figure 3.9: Hybrid grid.

In Figure 3.9, there is a sSLD for a configuration where the battery has been integrated directly into the DC-link of the VSD for the propulsion loads, utilizing a DC-DC converter. This results in fewer conversion stages, thereby increasing energy efficiency. It is also less expensive with a DC-DC converter than a DC-AC converter [46], which is necessary for Figure 3.8a. The DC-link with the battery connected to it can be seen as a DC-bus, and it is also possible to have only one battery connected to both VSDs. This approach may enhance flexibility in a retrofit by eliminating the need for direct connections to the main switchboard. This also makes it easier to achieve battery modes where it is necessary with rapid changes in the power flow from the battery to the propulsion. With this configuration, it will not be possible to supply anything else other than propulsion from the battery. To run a vessel fully electric, the battery must also be able to supply the auxiliary loads. The battery system needs to be integrated with the main switchboard, a process that elevates both the cost and complexity of retrofitting. However, the value of this undertaking may be justified by the intended results. Integration can be accomplished by incorporating a bidirectional AC-DC converter within the VSD. Alternatively, establishing a new connection from the battery to the main switchboard via a bidirectional AC-DC converter is feasible, although this approach necessitates additional cabling and components.



(a) DC grid 1, constant voltage on the main switchboard.

(b) DC grid 2, variable voltage on the main switchboard.

Figure 3.10: DC grid.

The SLDs in Figure 3.10a and Figure 3.10b illustrate two different electrical configurations with a DC main switchboard. The power output from the generators must be converted from AC to DC using an AC-DC converter. This allows for one of the advantages of DC switchboards as the diesel generators may operate more fuel efficiently by adjusting the speed to the required power demand and hence lower the specific fuel consumption [47]. In these two examples, the propulsion loads are AC electrical motors, and the power from the main switchboard gets inverted from DC to AC through DC-AC inverters. Additionally, the auxiliary loads are DC-AC inverted, and the transformer serves as galvanic isolation and provides voltage adjustment. The main difference between the two diagrams is that in Figure 3.10a, the voltage on the main switchboard is constant, and in Figure 3.10b, the voltage depends on the battery SOC and characteristics. Reducing the number of converters lowers costs and improves power efficiency but also introduces certain challenges. The power converters on the load side must operate within the main switchboard's entire voltage range. This sets more requirements on the characteristics of the components that are connected to the main switchboard, and it can be challenging to utilize the total battery capacity without a high minimum voltage on the battery [46]. Despite these challenges, certain studies have shown this to be the most promising integration approach with a DC main switchboard for many vessels, particularly for smaller vessels [46]. It also makes it easier to configure a reliable system that desirably utilizes the battery for the relevant battery modes without needing battery power converters to keep the voltage stable, making the control system more complex.

Use case results: Grid topology possibilities

This section aims to outline the evaluation process for eliminating some of the proposed electrical grid designs for the retrofit. This is done by evaluating the existing power grid in relation to the battery installation. The process will refine the possibilities down to only those that are feasible and most promising.

The power grid onboard RV Gunnerus, Figure 2.2, consists of a main switchboard powered by three diesel generators, generating 440 V at 60 Hz. There are also auxiliary loads and three AC propulsion electrical motors. In this preliminary phase, it is necessary to evaluate the different general solutions that have been proposed concerning the retrofit of the vessel with a BESS.

The MV solution illustrated in Figure 3.8b is not relevant to investigate further because of the physical size of RV Gunnerus, and the total power installed is too low.

The two DC electrical grid solutions proposed, one with constant voltage on the main switchboard, Figure 3.10a, and one with varying voltage, Figure 3.10b, are more promising than the MV solution and could be good solutions in general perspective. However, some challenges arise based on a comparison with the existing power grid. The electrical grid is now AC, and making the electrical grid DC would require multiple new components, tests, and requirements for the existing cabling, safety components, and converters. This might be feasible, but the added cost and complexity of the retrofit will most likely not be worth it. Therefore, despite possibly being optimized for fuel efficiency, these grid solutions will not be investigated further.

The two general solutions left are Figure 3.8a and Figure 3.9. The first is with the battery integrated into the main switchboard through a bidirectional converter. In the other, the battery is integrated directly to the DC-link in the VSD of the propulsion. These two general solutions are promising but have different challenges, strengths, and weaknesses. They will both be further discussed in the preliminary design phase with regard to the existing electrical grid onboard RV Gunnerus. More details will be considered, and multiple options will be offered within the two proposed general solutions.

4 Physical vessel integration

Having completed the concept design phase for a vessel retrofit with a BESS. The concept has proven potential for retrofit through a space analysis, a preliminary sizing strategy, an initial estimation of the potential fuel savings, and an evaluation of potential grid architectures.

In this chapter, the integration will be viewed from a physical perspective, evaluating the options for physical installation. This includes evaluating the best integration method, how the installation will affect stability and trim, and finally, requirements for the thermal safety management systems. This chapter will end with a discussion and a recommendation for the physical placement of the battery.

4.1 Battery dimension

This section will evaluate the battery design and required dimensions regarding weight and physical size. To determine this, the electrical size and the kind of battery design will be evaluated. Ultimately, the battery manufacturer states the actual weight and physical size. However, this section will provide an estimation of the battery size.

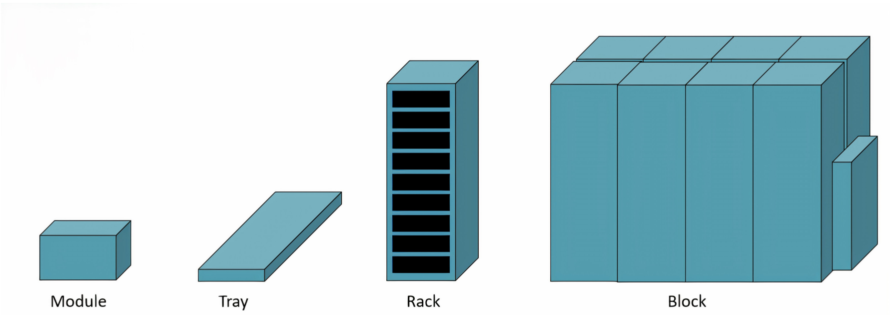


Figure 4.1: Different battery design [42].

There are 4 main types of battery design, illustrated in Figure 4.1, modules, trays, racks, and blocks. Where modules represent the greatest flexibility, and blocks represent the easiest integration. Module-based systems have modules that can be placed individually from each other, which provides flexibility. The modules have a certain output voltage, and the system voltage is determined by the number of modules in series. The flexibility makes it great for small battery rooms or smaller vessels. However, since the modules are placed individually, the integration of auxiliary equipment is more complex, e.g. cooling and ventilation. Trays are mainly from the automotive industry, and the maritime trays are usually automotive trays fitted for marine-type approval. It is less flexible since the output voltage from the tray is not meant to be connected in series. Rack-based systems have a predefined rack solution, where safety measures and cooling systems are integrated into the rack. There is some flexibility in the design of the rack, however, they are mainly bound to specific standard sizes. Block-based systems are usually entirely outfitted, making the integration relatively easy. The block contains all safety measures, monitoring, and cooling systems. This is typical for a container-based solution, where the block consists of multiple racks. However, these racks can not be placed individually [42].

SEABAT studied the different battery designs and tested 30 marine-approved battery systems [42]. The designs were tested for safety requirements, required service space, and

Table 4.1: Required service space for battery design [42].

Battery design	Required service space
Blocks	37 %
Trays	44 %
Racks	53 %
Modules	74 %

energy density in volume and weight. Racks and blocks scored best regarding safety due to their integrated safety systems, though modules and trays scored lower, it is entirely feasible to integrate, but it requires more effort in designing the safety systems. Service space is the required space for auxiliary equipment and space for inspection and maintenance. The values are given in percentage of the required floor service space compared to the battery floor space. The required service space for each design is given in Table 4.1. There are two main reasons that modules rank the worst. Firstly, the modules are the smallest unit, so the required service space is relatively big, and secondly, the modules come with no auxiliary equipment, so this must be mounted in addition. On the other hand, block solutions score the best, but they are bigger and require more space in total.

In the concept design, it was recommended that NMC batteries should be used. SEABAT tested for NMC, LFP, and LTO, and the density varies depending on the chemistry, for this evaluation only the NMC batteries are extracted to the table Table 4.2. The data for the calculations are based on [42]. Trays score overall best on both gravimetric and volumetric density, however, as space is often most limited, modules also score well on volumetric density. Note that only some auxiliary equipment is included in both racks and blocks, so the comparison is not completely unbiased.

Table 4.2: Energy density for NMC batteries.

Battery design	Density volumetric [Wh/L]	Density gravimetric [Wh/kg]
Blocks	67	86
Trays	168	121
Racks	86	94
Modules	119	140

4.1.1 Use case results: Battery dimension

The tray design does not usually include the possibility of series connection to increase the system voltage, therefore, it is not be considered a feasible option because it does not comply with the overall goal of FLEXSIP. However, the three other options are feasible, and Table 4.3 illustrates the weight and volume of the battery, for the two electrical sizes. The required service space is not included, as this depends on the floor area of the battery, which is not defined at this point. Furthermore, the service space is highly reliant on the manufacturer, and some of the required service space may be placed outside the battery room. Table 4.1 is included to give an idea of the necessary space for auxiliary equipment and availability for inspection and maintenance.

Table 4.3: Volum and weight for RV Gunnerus batteries.

Battery design	**1 MWh Battery**		**2.5 MWh Battery**	
	Volume [m^3]	Weight [tonn]	Volume [m^3]	Weight [tonn]
Block	14.9	11.6	37.3	29.1
Rack	11.6	10.6	29.1	26.6
Module	8.4	7.1	21	17.9

Regarding weight and volume, a module-based design is preferable. The module design offers great flexibility, however, safety monitoring and cooling are not included in these calculations. A strategy for choosing a design could be to check for racks or blocks first, and if they do not fit, then check if a module-based design can fit.

4.2 Hydrostatic evaluation

Physical components installed on the ship can significantly alter the ship's weight distribution and center of gravity if not properly evaluated. When retrofitting a vessel, there may be limited options regarding available areas to use as battery space, reducing the possibility of placing the heavy battery in an optimal position. A correct stability evaluation for the placement of the batteries will ensure that the vessel remains safe and seaworthy under all operating conditions.

Stability-related requirements are described under RINA Rules Part B, Chapter 3, Section 2. A summary of the basic stability criteria is given in Table 4.4. The general stability criteria describe the requirements related to the righting lever curve (GZ curve) and θ (the angle of heel), [48].

$$GZ = KN - KG \cdot \sin\theta \tag{11}$$

Table 4.4: Stability requirements cargo ship.

Requirements	**Value**
1. Min. GZ at angle 30°or more	0.200 m
2. Min. angle for GZ max	25°
3. Min. GM	0.150 m
4. Min. area under GZ curve 0-30°	0.055 m rad
5. Min. area under GZ curve 0-40°	0.090 m rad
6. Min. area under GZ curve 30-40°	0.030 m rad

When a vessel is floating in a steady position, the mass center (G) is directly above the buoyancy center (B). When the vessel is heeling to one side, the gravity center is still the same, but the submerged part of the hull is different, and this gives a new temporary buoyancy center. This difference in the gravity center and buoyancy center is most often the force that rightens the vessel. As shown in Figure 4.2 the GZ value represents this righting lever when the vessel is heeling. It is defined by the horizontal distance between the vessel's center of gravity and a vertical line going through the temporary buoyancy center caused by the healing [48]. When the ship is heeling with small angels the point in which the vessel is rotating around is called the metacenter (m). As long as the GM value is positive, the vessel will tilt back to an upright position when it is heeling. Large GZ

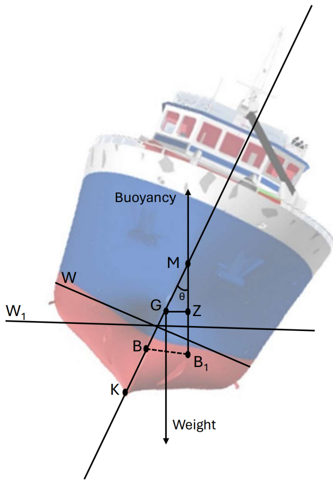


Figure 4.2: Ship stability.

values result in a stiff ship, meaning that it has good stability and can handle rough seas, but it can also be jerky and put a strain on the cargo and the crew. On the other hand, if the GZ values are small the ship will be tender, meaning that the ship is still stable, but it has less excess rightening lever. Resulting in a ship that will roll more and not be as quick in its righting movement.

A stability evaluation should be based on previous or new inclination tests, along with corresponding hydrostatic reports. Ideally, all operating conditions should be evaluated to determine the margins for each scenario and have a more complete picture of how the retrofit impacts the ship's stability. As an initial assessment, it is also possible to evaluate only the most precarious loading conditions and see how the battery placement may influence the ship's stability. Some important factors that influence a vessel's stability are the effects of wind, icing, and free surface area in the tanks. The class societies are responsible for determining the stability requirements for different ships, including the necessary safety margins.

The fore-and-aft balance of a ship is called longitudinal trim, and it is critical for efficient maritime operations. An optimal trim enhances propulsion efficiency, maintains structural integrity by distributing stress evenly along the hull, and improves maneuverability by affecting the hydrodynamic flow. It also contributes to better seakeeping by minimizing pitching, ensures compliance with draft restrictions for safe port entry, and optimizes stability, which is crucial for safety in rough seas. Additionally, a well-managed trim can lead to reduced fuel consumption, lowering operational costs [49]. Thus, carefully managing the battery placement in the longitudinal direction is essential to achieve the desired trim for safe and economical vessel operation. The draft combined with the trim will also affect how the vessel moves in the roll motion, which is more important regarding stability than the pitch motion. It should be noted that the added weight of a battery will cause an increase in the vessel's draft, leading to an increased drag due to more of the vessel's surface area being submerged. Consequently, this will affect the vessel's load profile, in terms of fuel consumption at various speeds. This effect is unavoidable and could influence the sizing of the battery due to new load profiles for the vessel. Therefore, the correct battery size should be further investigated, especially if a relatively heavy battery is chosen compared to the total weight of the ship.

To discern the impact various battery placements can have on ship stability, an examination of how the additional weight affects the ship must be conducted. Whether a placement is feasible or not, can be simplified to calculating if the new KG is within KG_{max} curves. These curves represent the maximum KG for different draft and trim, under different loading conditions, to comply with the requirements presented in Table 4.4. Three parameters must therefore be calculated with the added weight of the battery, the new trim, the new draft, and the new KG. The trim and the draft are used to find the maximum allowed KG, and the KG must be within the maximum KG. The new KG is calculated using Equation 12, where the impact of the additional weight is determined in terms of change in the vertical center of gravity. To calculate the new draft Equation 13 is used, with the tonnes per centimeter immersion (TPC) value for the given loading condition. The TPC describes how much weight, in metric tonnes, needs to be added or removed to change a ship's draft by one centimeter. The TPC indicates the ship's sensitivity to loading and unloading, at the given loading condition. When a new draft is established, the trim moment (MT1) value can be found in the stability book for the ship, the MT1 indicates how much moment in tonnes per meter is required to change the vessel's trim by one centimeter for a given loading condition. The added trim, compared to the original trim for the given loading condition, is calculated using Equation 14.

$$KG_{New} = \frac{KG_{ship} \cdot \Delta + KG_{batt} \cdot M_{battery}}{\Delta + M_{battery}} \tag{12}$$

$$d_1 = \frac{M_{battery}}{TPC} + d_0 \tag{13}$$

$$t_{added} = \frac{M_{battery} \cdot (LCB_{ship} - LCG_{battery})}{MT1} \tag{14}$$

4.2.1 Use case results: Hydrostatic evaluation

This stability evaluation for RV Gunnerus will be conducted using the existing hydrostatic report completed on February 02, 2019, by Polarkonsult. Seven loading conditions were investigated, and a brief overview of the results is shown in Table 4.5. The most relevant parts of the report can be found in Appendix C. The report includes KG_{max} curves which are based on the Det Norske Veritas (DNV) requirements for ship stability. These requirements are the same as the ones RINA uses, for this type of vessel.

Table 4.5: Loading conditions from inclination test of RV Gunnerus.

No.	Tekst	Bro	FV	VB	Div	Utr	Rom	Dekk	RD	Pers	DW (t)	d, mld (m)	Trim (m)	GM (m)	KG marg (m)
1	Lett utrust, 100%	49.5	59.6	0.0	5.5	7.5	0.0	0.0	8.5	0.0	130.6	2.687	-0.402	1.792	1.063
2	Lett utrust, 10%	5.0	5.7	0.0	18.3	7.5	0.0	0.0	8.5	0.0	44.9	2.321	0.439	1.895	0.732
3	Tungt utrust, 100%	49.5	59.6	0.0	5.5	43.8	0.0	0.0	8.5	2.0	168.9	2.786	-0.011	1.634	0.622
4	Tungt utrust, 10%	5.0	5.7	0.0	18.3	43.8	0.0	0.0	8.5	2.0	83.3	2.421	0.831	1.684	0.294
5	Max Dekkslast, 100%	49.5	59.6	0.0	5.5	7.5	0.0	38.5	8.5	0.0	169.1	2.786	-0.002	1.608	0.593
6	**Max Dekkslast, 10%**	**5.0**	**5.7**	**0.0**	**18.3**	**7.5**	**0.0**	**38.5**	**8.5**	**0.0**	**83.5**	**2.421**	**0.841**	**1.654**	**0.259**
0	Lett skip	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.169	0.364	2.262	

It is clear from the report by Polarkonsult, that the ship has an aft trim for most loading conditions. The KG_{MAX} curves show that the vessel has the lowest KG margin with the highest positive trim, meaning the most aft trim. The inclination test indicates that the most precarious condition regarding stability, i.e. the one with the lowest KG margin and most uneven trim, is loading condition 6. In this condition, the vessel is loaded with maximum deck cargo, and retains 10% of its fuel oil and fresh water capacity, in addition to general equipment, scientific equipment, and crew. More details can be found in Appendix C. This results in a total of 83.5 t dead weight added compared to the lightship condition. KG_{MAX} in this loading condition is from the hydrostatic report found to be 4.068 m. In each tank containing a fluid, the maximum free surface effect has been accounted for in the calculations. In this condition, RV Gunnerus has a trim of 0.842 m and a mean draft of 2.421 m.

From the battery sizes estimated in Table 4.3, the stability impact on RV Gunnerus is calculated. This analysis will use a weight of 12 tonnes for the 1 MWh battery system and 30 tonnes for a 2.5 MWh battery system. These weight estimations encompass all subsystems related to the battery space. It has not been considered that RV Gunnerus has 10 tonnes of fixed ballast in its bow, some of which could potentially be removed if the battery is integrated into the forward part of the vessel. This adjustment could effectively reduce the weight impact of the battery integration. The battery placements are based on measurements from the general arrangement document, shown in Appendix D. Calculations on KG, draft, and trim were done under loading condition 6, and resulted in a new mean draft of 2.463 m for the 1 MWh battery system and 2.526 m for the 2.5 MWh battery system. From the hydrostatic data with a 0.75 m trim the battery systems get a MT1 equal to 6.73 $MT{\cdot}m/cm$ and 6.77 $MT{\cdot}m/cm$ correspondingly. With this approach, a new draft and trim are obtained for each battery location, and these results are used in the KG_{MAX} curves to estimate the stability margin for each option. The results are shown in Table 4.6 with corresponding calculations in Appendix E.

Table 4.6: Results from battery stability evaluation regarding KG and ship trim.

	1 MWh, d = 2.463 m		**2.5 MWh, d = 2.526 m**	
	Trim [m]	KG margin [m]	Trim [m]	KG margin [m]
Aft cargo hold	1.037	0.114	1.328	-0.037
Engine room	0.878	0.215	0.954	0.187
Dry provision	0.563	0.370	0.151	0.548
Living quarter 1. Deck	0.563	0.312	0.151	0.408

This stability evaluation, based on Polarkonsult's hydrostatic report from 2019, demonstrates that all the battery space locations proposed are well within the margins of the RINA rules, except for a 2.5 MWh battery in the aft cargo hold.

- The aft cargo hold location, Figure 4.3, is an option with enough available space, and it would not directly affect any other systems, on the other hand, it is the alternative with the lowest stability margin regardless of battery size, and it will further increase the vessel's aft trim.

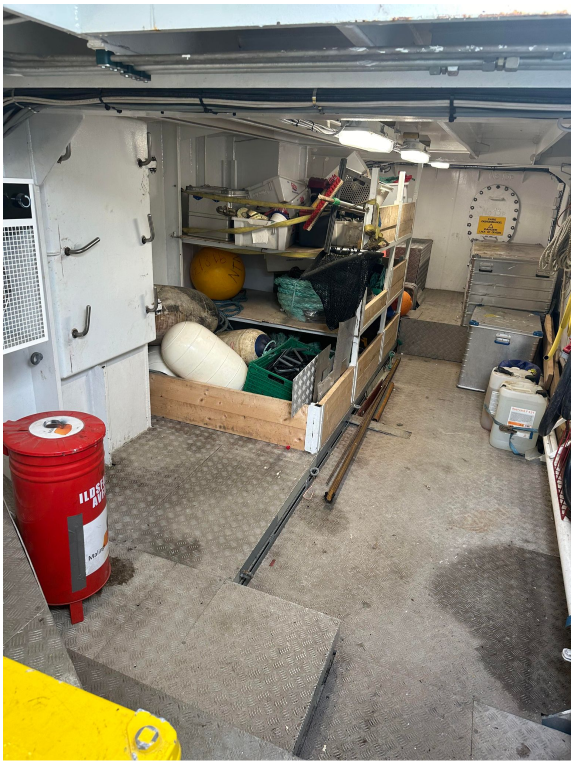


Figure 4.3: The aft cargo hold.

- For the engine room option, Figure 4.4, the battery location is relatively close to the current ship LCG, and in addition, the weight of the integration will be lower due to the removal of one diesel generator. This results in the lowest change in stability compared to the current situation. It is also the condition with the shortest distance from the main switchboard. On the downside, it is not a good option to underscore the overall FLEXSHIP goal due to the necessity of removing a diesel generator. Removing a diesel generator will require significant work and ultimately reduce the existing power capability and redundancy. However, it could be argued that two diesel generators and a BESS would be sufficient for all of RV Gunnerus' normal operations.

Figure 4.4: Port side of the engine room, showing one of the three diesel generators.

- The living quarter in the forward part of the ship on deck 1, Figure 4.5, is the only option that has a vertical center of gravity (VCG) higher than the current vessel KG, impacting the vessel stability negatively. However, the vessel's stability regarding GM and a heightened KG is not an imminent threat, and from the calculations, the vessel will get an increased KG margin due to a more forward trim. This option will sacrifice a cabin, which might be unpopular with the crew. Most of the room is also on the port side of the vessel, which might make the vessel heal to port. To counter this healing, installing some fixed ballast on the starboard side might be necessary, resulting in a heavier total installation.

Figure 4.5: The living quarter in the forward part of the ship, on deck 1.

- The Dry provision room, Figure 4.6, is the smallest suggested room with a volume of only 12.5 m^3. By comparing the available space with the Table 4.3, it can be seen that the smallest battery module design is the only feasible option for this room. The rack design appears possible, but the requirement for service space renders the rack solution infeasible. However, the energy density data are based on the Seabat report. Some of the batteries investigated in the report performed much better concerning volumetric density, and the batteries used by FLEXSHIP will likely not be average batteries. Therefore, a final discussion with the chosen manufacturer is needed to investigate feasibility.

If more space is necessary, the "linen" room on the port side could be incorporated. Utilizing the dry provision room as battery space would result in a loss of storage space for the crew, but it is not a significant loss. If this option is feasible, it would greatly reinforce the FLEXSHIP core objectives of being flexible and modular.

Figure 4.6: The dry provision room.

4.3 Safety management

In the risk assessment, subsection 2.5, it was identified that one of the major concerns regarding lithium-ion batteries onboard vessels is thermal runaway. It is important with a well-functioning thermal management system, to give the battery good operating conditions, and to prevent the occurrence of thermal runaway. The ventilation system and the BMS must work as intended, by keeping the battery within the desired values. In addition to preventive measures, it is also important with emergency safety measures that can stop an undesirable event from developing further.

Thermal runaway

Thermal runaway is a self-propagating exothermic reaction within a lithium-ion battery [11]. This can be caused by mechanical abuse from external stresses, such as collisions or penetration of the casing, leading to a short circuit. It can also be caused by electrical abuse, such as overcharging or excessive discharging, contributing to dendrite growth, which will cause an internal short circuit if it grows through the separator [50]. Thermally, lithium-ion batteries can overheat due to internal electrochemical reactions or external heat sources, as shown in Figure 4.7. These factors can trigger a chain of exothermic reactions, rapidly increasing the battery's internal temperature. This can culminate in a thermal runaway event, potentially causing smoke, fire, and explosions [10]. Suppressing thermal runaway events is crucial for enhancing lithium-ion battery safety. Given the critical safety requirements of their applications, devising methods to detect and assess lithium-ion battery safety has become a significant challenge for both industry and academia [10].

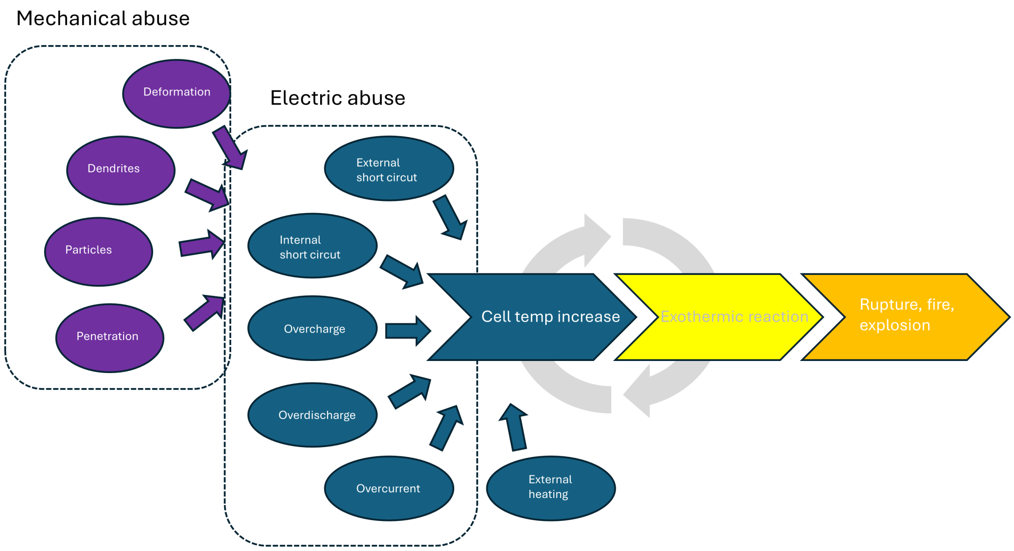


Figure 4.7: Sources of exothermic reactions lithium-ion battery, based on [11].

Thermal management systems are defined as systems necessary to ensure that the battery operates at the right temperature by regulating the cooling or heating flow [13]. The system might utilize either air cooling or liquid circulation. A liquid cooling system is assumed to be more expensive, and heavier than air cooling, but it gives better temperature control of the battery, and the battery manufacturer might require it to ensure the safety of the battery. Some liquid cooling systems on the market are so effective that it is practically impossible for a cell to go into thermal runaway as long as the system is active [42]. A liquid cooling system, according to RINA Rules Part C, Chapter 2, Appendix 2, section 4 will require at least two pumps for each primary and secondary circuit, it is also important to minimize the risk of cooling liquid leakage inside the module. If a liquid cooling system is chosen, a ventilation system for the battery space is still necessary to extract off-gas. Lithium-ion batteries are sealed systems that do not generate off-gas during normal charging and discharging. However, as described, a range of abusive factors affecting a battery cell can lead to the electrolyte starting to decompose and subsequently to the formation of gases inside the cell. Tests have shown that gases produced are likely to be both toxic, flammable, and potentially explosive [12]. This means that the ventilation system must be able to vent out gases from the battery space. It also needs to be capable of venting out explosive gases in case of a fire. These characteristics must be considered in the design of the battery space and its ventilation system. The design should prevent the accumulation of flammable gases and the dispersion of toxic gases into other ship compartments. The utilization of sensors for off-gas detection is vital. According to RINA Rules Part C, Chapter 2, Appendix 2, section 4, the battery spaces must have a forced ventilation system of extraction type, which is to be:

- independent from any other ventilation system serving other ship's spaces,
- provided with local manual stop, still available in case of failure of the automatic and or remote control system,
- provided with indication of ventilation running and of battery space ambient temper-

ature,

- with a capacity (rate) according to battery manufacturer guidelines on the basis of the gas release identified in the gas analysis or propagation test,
- fitted with inlet from open air,
- fitted with exhaust outlet to open air far from accommodation and machinery ventilation inlets,
- fitted with non-sparking fans driven by a certified safe type electric motor in case the ventilation duct is considered to contain an explosive atmosphere in case of thermal runaway.
- an alarm at 30% of lower explosive limit (LEL) and automatic disconnection of batteries are to be provided,
- an alarm at 60% of LEL and automatic disconnection of all electrical equipment non certified of safety type for the specific hazardous area, gas, vapor are to be provided.

In the event of an uncontrolled cell temperature increase, potentially escalating to an exothermic reaction, it is crucial to prevent rapid spread to adjacent cells and modules. RINA Rules Part C, Chapter 2, Appendix 2, section 4 does not have specific requirements, but it states that "The design and construction of battery modules have to reduce the risk of a thermal propagation due to a cell thermal runaway, maintaining it confined at the lowest possible level (e.g. confined within a module). This may be achieved using partition plates or sufficient distance in accordance with maker recommendation to prevent escalation between battery modules in case of a thermal runaway.". The primary defense against this is the implementation of thermal runaway propagation insulation. This involves not just real-time monitoring of the battery's condition to detect the onset of thermal runaway, but also the adoption of measures to arrest its spread once detected. Enhancing the safety of lithium-ion batteries at the cell level (internal protection) and using barrier technologies throughout the battery (external protection) are the two most typical methods to slow down the thermal runaway propagation process [12]. Different types of battery thermal management systems might also be used to lower the temperature and slow down the exothermic process in the case of thermal runaway [11].

The RINA Rules Part C, Chapter 2, Appendix 2, section 4, states that it is necessary with a fire detection system and a fixed fire extinguishing system. The fire extinguishing system can for example be a powder, gas-based, or water-based fixed fire extinguishing system provided that the suitability of the extinguishing agent for the specific type of batteries is confirmed by the battery manufacturer. Automatic release of the fixed fire extinguishing system can decrease the probability of a larger fire, but it is only acceptable for small, not accessible, battery spaces. With such a system more than one sensor must activate before the fire extinguishing media is released.

Monitoring and alarms

To reduce the risk of thermal runaway and improve the safety of lithium-ion batteries the BMS is crucial. It is important with correct monitoring and alarm systems to ensure the safety of the battery. The RINA Rules Part C, Chapter 2, Appendix 2, section 3, set the rules for what is necessary to comply with in this retrofit. The BMS and related safety systems need to have self-check function, meaning that in the event of a failure in for example a sensor, an alarm is activated. The BMS must be powered so that a single failure in the power supply does not cause any degradation of the BMS functionality, and an alarm is to be activated in case of a failure of any of the power supplies. It is the BMS that sets the limits for charging and discharging, it disconnects the battery in case of over-current, over-voltage, under-voltage, and over-temperature. It also provides cell and module balancing. The parameters that the BMS must continuously monitor and display at a local control panel are:

- system voltage
- max, min, and average cell voltage
- max, min, and average cell or module temperature
- battery string current
- SOC and state of health (SOH)

Abnormal conditions that can develop into safety hazards must activate an alarm before reaching the hazardous level. These are the minimum required alarms listed by RINA:

- safety intervention of the BMS of the battery system
- high ambient temperature,
- failure of cooling system or leakage of liquid cooling system
- low ventilation flow inside the battery room
- over-voltage and under-voltage
- cell voltage unbalance
- high cell temperature
- other safety protection functions

It is crucial to recognize that a BMS is more than just a collection of electronic parts managing battery charge or monitoring its health. A simplistic view can lead to designs that do not meet the necessary specifications, cost goals, or particular safety requirements. A BMS should include all vital components, functions, and features needed to meet the performance, environmental, and safety standards of the specific battery and the system it serves. Finally, the BMS needs the ability to disconnect the battery in case of an exceeded warning value. There can be no risk that this is overruled by any other part of the control system.

Constructional requirements

Constructual requirements given by RINA when implementing a lithium-ion battery can be found in the RINA Rules Part C, Chapter 2, Appendix 2, section 2. Battery cells of different chemistries must not be used in the same electrical circuit. It states that the battery enclosure covering modules and cells must be made of flame-retardant materials. It must have a thermal protection device that can disconnect the battery in case of high temperature. There must also be an emergency shutdown system installed capable of disconnecting the battery system in an emergency. In addition to the emergency disconnection, an independent device to disconnect the battery and isolate it for maintenance purposes must be installed. If the fire extinguishing system is water based IP44 is required as a minimum for equipment used in the battery space. Additionally, if the battery space is below the freeboard deck, the risk of water immersion must be considered, and the batteries must have a minimum protection rating of IPX7. The rating IPX7 means that the equipment must be able to withstand being submerged in up to 1 m of water for 30 minutes without any damage. The battery space must have self-closing doors, or as an alternative, it can have a normally closed door with an alarm being activated if it is not closed. In the RINA Rules Part C, Chapter 2, Appendix 2, section 4 it is stated that "Batteries are to be arranged aft of collision bulkhead and in such a way that danger to persons and damage to the vessel due to failure of the batteries (e.g. caused by gassing, explosion, and fire) is minimized." This implies that the chosen battery space can not be in the very front of the vessel, and if there are any cabins close to the battery space this should be taken into consideration regarding personnel safety.

4.3.1 Use case results: Safety management

The dry provision room is placed in the forward part of the ship on the "Bellow 1-Deck" partially submerged under the water line. The room adjoins the forward bulkhead with the bow thruster in the front. In the back, it adjoins a storage room and the living quarter hallway in the aft. Below is a technical water tank and above there are living quarters.

Based on RINA rules and regulations regarding safety management discussed earlier in this section, the most important requirements applicable to the selection of battery space location for the use case are as follows:

- The batteries must have a minimum protection of IPX7 if the battery space is below the freeboard deck, and the risk of water immersion has to be considered.
- The room needs to be fitted with a self-closing door, or a door that is normally closed with an alarm.
- It must have a thermal protection device, that disconnects the battery in case of high temperatures.
- There must be an emergency shutdown system installed separately from the isolating device for maintenance. The system must be hardwired, and independent of the control system.
- The ventilation system must be an independent system separated from any other ventilation on the ship. It must also have both the inlet and the outlet directly to open air, and the outlet can not be in proximity to accommodation or machinery ventilation inlets.
- Correct and safe implementation of cooling, ventilation, and electrical components such as BMS will have to be planned together with the battery manufacturer.

4.4 Discussion and recommendation for physical integration

Firstly, four different battery designs were evaluated, with the module design representing the most flexible solution and the block design representing the easiest integration, given enough available space. RV Gunnerus does not have a lot of excess space, and in addition the FLEXSHIP goal states that their solutions will be flexible, modular, and scalable. With this in mind, the modular battery design is the best choice. Considering ship stability, only the 2.5 MWh battery placed in the aft cargo hold is infeasible. The most favorable placement regarding stability is the living quarters or the dry provision room. The engine room placement represents a solution that will change the current trim the least due to its proximity to the ship's center of gravity. The aft cargo hold implies more aft trim, which is within the requirements, but it decreases the ship's seaworthiness. The most favorable solution is the dry provision room, as the living quarters reduce the cabin space and might force a more port trim. Due to volumetric limitations, the only feasible battery in the dry provision is a 1 MWh battery, with a module design. Regarding the 2.5 MWh battery, neither the dry provision room (12.5 m^3) nor the living quarters (20.1 m^3) are feasible due to the size of the rooms. A 2.5 MWh battery is feasible for the engine room, but it does not comply with the stakeholders' desired outcomes regarding flexible and modular design. It will also be necessary to remove one diesel generator, reducing the ship's redundancy and increasing costs.

The physical analysis presented in this chapter concludes that a 1 MWh module battery design situated in the dry provision area is the best solution for the use case. Due to constraints in placement options, the 2.5 MWh battery option is deemed impractical. Consequently, the objective of sailing 50 nm fully electric is no longer pursued.

With the chosen battery space being the dry provision room, might pose some significant challenges:

- The room is small and narrow.
- It is partially below the vessel's waterline.
- The ventilation system's inlet and outlet must be directly to open air.
- It can not be in proximity to accommodation or machinery ventilation inlets.
- The room is near existing living quarters.
- It is far from the main switchboard.

The size of the room is a challenge, but it underscores the FLEXSHIP goal if it is feasible, and the vessel sacrifices the least amount of space. The room being partially submerged needs to be taken into account in terms of risk assessment and additional safety measures. The ventilation system will likely be required to go through other adjacent rooms to avoid the inlet and outlet being on the side of the ship and close to the waterline. The existing ventilation inlet for accommodation and machine room is located aft of the navigation bridge, this must be taken into account regarding the placement of the battery room ventilation in order to comply with RINA rules. The room is close to living quarters, and extra measurements should be made concerning personnel safety with regard to thermal runaways and explosions in a worst-case scenario.

If the mentioned challenges prove to be too difficult to solve, a good option for battery space location is the living quarter, in the forward part of the ship on deck 1. The room is larger, it is above the water line, and the installation of an independent ventilation system is assumed to be easier. Even though the room is above the vessel's VCG, it does not influence the vessel's stability negatively due to the positive effect of a more forward trim.

5 Electrical vessel integration

Having completed the first iteration of the physical preliminary design, the next part will concentrate on the electrical aspect of the retrofit. The concept design established the boundaries for the electrical vessel integration, alongside the physical preliminary analysis. The most important factors to consider regarding the electrical aspect of a BESS integration include grid topology, power quality, shore-to-ship connection, protection, and selectivity.

This chapter will first investigate possible grid topologies for implementing a BESS. The two general solutions presented in the concept design phase, subsection 3.5, are further elaborated and discussed. These grid solutions are evaluated in relation to the existing grid onboard RV Gunnerus and the goals and objectives for the retrofit. Furthermore, power quality challenges concerning isolated ship micro-grids are presented, along with possible solutions relevant to RV Gunnerus. Additionally, options for shore-to-ship connection (S2S) with their challenges and opportunities are discussed. Finally, some challenges regarding power grid protection and selectivity are elaborated. This chapter concludes with a discussion and a recommendation for an electric power grid.

5.1 Power distribution: Grid topology

Based on the initial evaluation conducted during the concept design phase, as referenced in subsection 3.5, two general solutions have been selected, one AC grid and one hybrid grid, as depicted in Figure 3.8a and Figure 3.9. In this section, these two general solutions will be further investigated as alternatives to the existing electrical grid on RV Gunnerus. Proposals for different options and possibilities associated with the two solutions will be presented, and their strengths and weaknesses will be discussed.

The AC grid solution is applied to the existing electrical grid of RV Gunnerus in Figure 5.1, and the hybrid grid solution is used in both Figure 5.3 and Figure 5.4. These options represent different ideas for how the battery may be implemented and various configurations of these options will also be discussed. The black lines indicate what is already on RV Gunnerus, and the blue lines are retrofit suggestions.

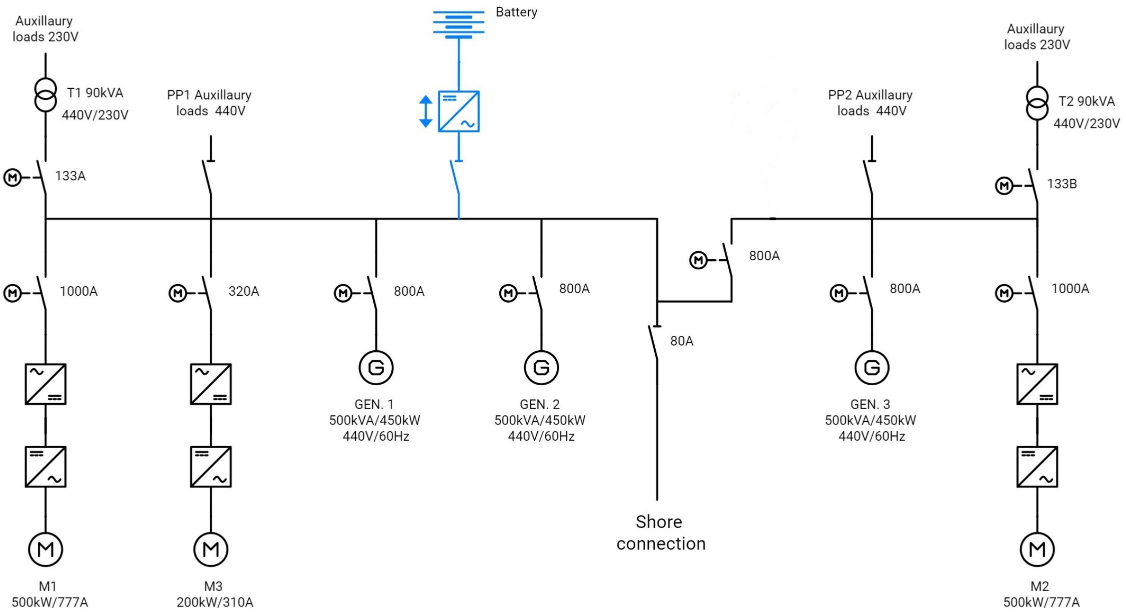


Figure 5.1: AC grid RV Gunnerus.

AC grid

In Figure 5.1, the battery is connected to the main switchboard through a bi-directional AC-DC converter. This converter allows energy to be both supplied to and from the battery, a capability necessary for achieving the desired result. As illustrated by Figure 5.1, this can be achieved using one battery and one converter connecting the battery to one side of the main bus bar. This configuration represents the most straightforward solution but also offers the lowest redundancy and might prove more difficult in terms of the control aspect.

In the scenario where the main bus tie is open, only one side of the grid could be supplied by the battery. Adding another converter to the same battery would enable it to supply both sides in an open bus-tie scenario, though this increases complexity and cost. Alternatively, the battery pack could be split into two, with each battery connected via a converter to each side of the main switchboard. This option provides the highest redundancy but involves the most components. This setup allows for the full usage of the battery even with an open bus-tie connection.

(a) AC grid without a DC-DC converter.

(b) AC grid with a DC-DC converter.

Figure 5.2: AC grid with and without a DC-DC converter.

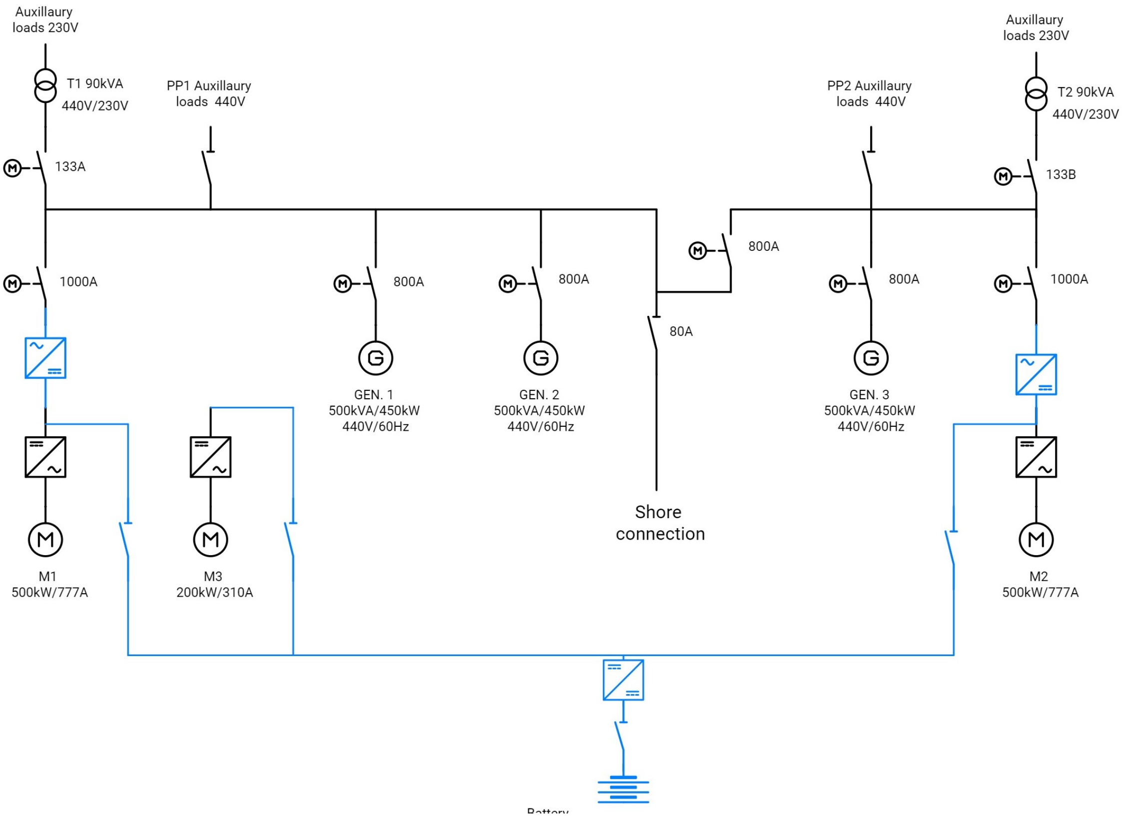


Figure 5.3: Hybrid grid 1 for RV Gunnerus.

As the converter must be bi-directional an AFE converter is typically employed. Although diode rectifiers are known for higher reliability [51], they are not optional due to their inability to both charge and discharge the battery. An auxiliary converter, as proposed by [52], can be added to allow not only charging but also discharging. However, this setup necessitates that the total battery power passes through the active auxiliary converter, making it an ineffective solution. An active bidirectional converter is the suggested converter for this solution.

The battery exhibits a varying voltage depending on its SOC. Consequently, the option to install a DC-DC converter between the battery and the AC-DC rectifier, as shown in Figure 5.2b, exists. This installation allows the DC voltage seen by the AC-DC rectifier to be stabilized and permits boosting of the battery voltage, thereby granting greater flexibility in choosing the AC-DC converter.

In cases where there is a high AC grid voltage and a low DC voltage, installing a DC-DC converter could prove advantageous, despite the potential losses from adding another converter. This will be beneficial if it allows the DC-AC converter to operate in more optimal voltage areas.

Hybrid grid 1

In Figure 5.3, a SLD for hybrid grid 1 is presented, illustrating a configuration where the battery is integrated directly into the DC-link of the propulsion VSDs, using DC-DC converters. The connection of the battery to the DC-link of the VSD with a DC-DC converter might simplify the achievement of the desired outcomes for the BESS integration, such as *enhanced dynamic performance*. This is due to the reduced number of conversion stages between the battery and the propulsion load [12], and the possibilities concerning the control aspect.

For the vessel to operate fully electric, the battery must be capable of supplying the auxiliary loads. To achieve this, the battery must be able to supply the main switchboard. This can be accomplished by substituting the AC-DC rectifiers in the VSDs with bidirectional ones. In Figure 5.3 this has been proposed by changing the propulsion diode rectifiers to AFE converters. This modification allows the battery to supply power to the main switchboard and might also simplify the retrofit by enabling the replacement of existing equipment with new components.

The bow thruster may be integrated in several ways. It can be connected to the AC grid, as it is today, this solution minimizes changes in the existing grid. However, with this setup, the generators will supply the power demand for the thruster due to the power control. Only in fully electric operation would the battery supply power to the bow thruster.

Since the bow thruster is a relatively big power consumer, it is advantageous to be able to use battery power for its operation. To enable this, the DC-link for the bow thruster should be connected to the DC-bus. This can be done by replacing the diode rectifier for the bow thruster with an AFE converter and connecting it to the DC-bus. This solution introduces better redundancy, but higher cost and increased integration complexity. As hybrid grid 1 has two power supplies to the DC-bus, there is no need for a third, and the DC-AC inverter for the bow thruster may be connected solely to the DC-bus, as illustrated in Figure 5.3. This requires that the DC-AC inverter can handle the same voltage region as the DC-bus. The existing AC-DC diode rectifier may be removed, or at least disconnected from the AC-bus. This solution enables power supply both from the battery and the generators through the DC-bus.

Hybrid grid 2

Another option to ensure that the battery can supply power to the main switchboard is proposed in Figure 5.4. In this alternative, a new AC-DC inverter from the main switchboard to the DC-bus is installed. This means keeping the existing diode rectifiers and adding an AFE scaled to supply the hotel load. This option would require the smallest changes to the existing grid. The relatively low hotel load, in comparison to the propulsion, requires a much smaller AFE than the ones needed for hybrid grid 1. AFE's are both bulky and expensive [53], and if the battery integration can be done without changing to these, it would be economically beneficial. Additionally, as discussed earlier, diode rectifiers are passive converters and are more reliable than active converters.

The integration of the bow thruster can be done either directly to the AC-bus, but as discussed under hybrid grid 1, this is not a very flexible solution regarding power supply. In order to connect it to the DC-bus, the existing AC-DC diode rectifier for the bow thruster must be removed. Multiple diode rectifiers in parallel increase the integration complexity, as small changes in impedance in the three rectifiers, change the power distribution. As the rectifiers are passive, there is no direct control over the power through each of them. The recommended bow thruster integration is without any connection to the AC-bus, and the DC-AC inverter must be in the same voltage range as the DC-AC inverters for the main propulsion.

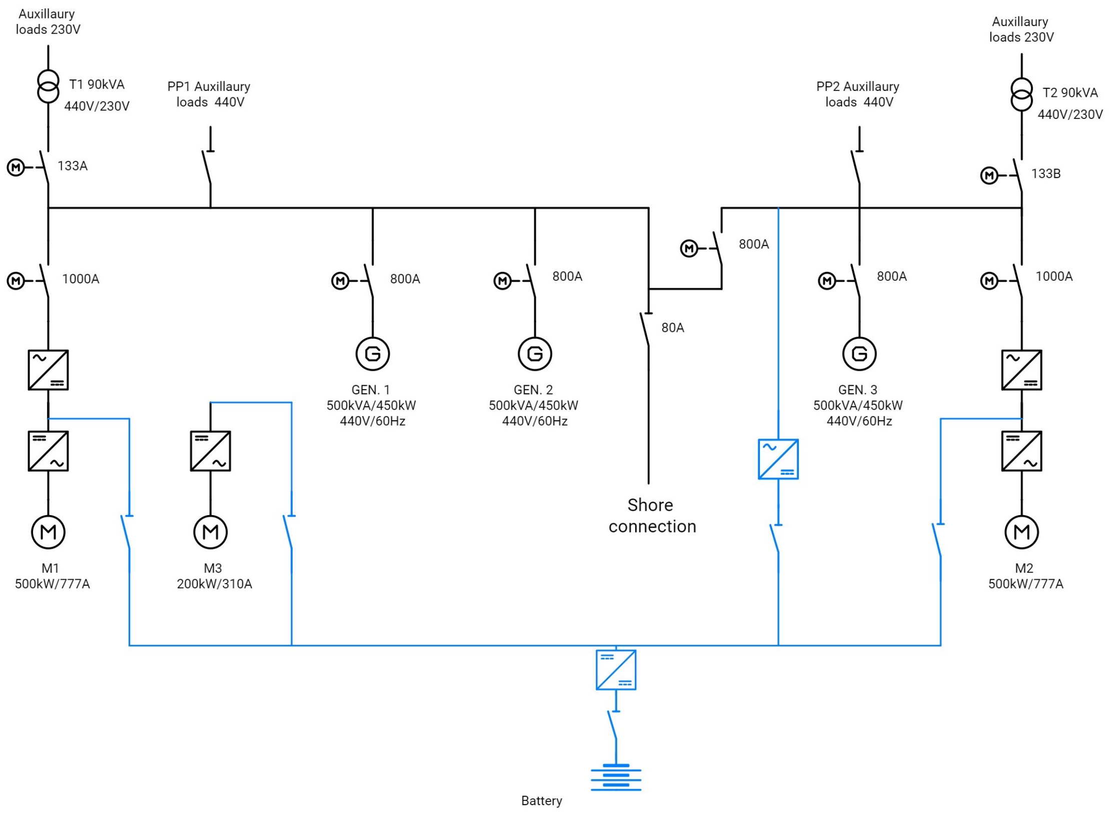


Figure 5.4: Hybrid grid 2 for RV Gunnerus.

5.1.1 Use case results: Grid topology

The existing electrical grid of RV Gunnerus, as shown in Figure 5.5, features a LV AC main switchboard with a three-wire 440 V, 60 Hz, ungrounded system. This robust grounding system is common onboard ships because it requires two grounding faults for a voltage potential to exist [54]. The main switchboard can be divided into two separate parts using a switch, enhancing redundancy. If there is a critical failure in one part of the electrical system, the affected part can be disconnected, and the propulsion and hotel loads can still be maintained.

Auxiliary loads on 230 V have redundant connections and are fed through a transformer, which provides galvanic isolation and allows for voltage adjustment. However, auxiliary loads on 440 V are only connected through switches and lack redundant connections. If the main switchboard is split, the 440 V consumers on the disconnected side will lose power.

The current power sources include three 500 kVA Nogva-Scania diesel generators connected to the main switchboard via switches, without power converters. These switches allow isolation of each diesel generator, but no converters or transformers are present to adjust the generated voltage. If the switchboard is divided, the starboard side will only have access to diesel generator 3.

The propulsion system comprises two 500 kW Rolls-Royce azimuth thrusters and a 200 kW Brunvoll bow thruster. These are connected to the main switchboard with VSD power converters, which rectify the current to DC and then invert it to the desired AC output in terms of both magnitude and frequency. The bow thruster is connected only to the port side of the switchboard.

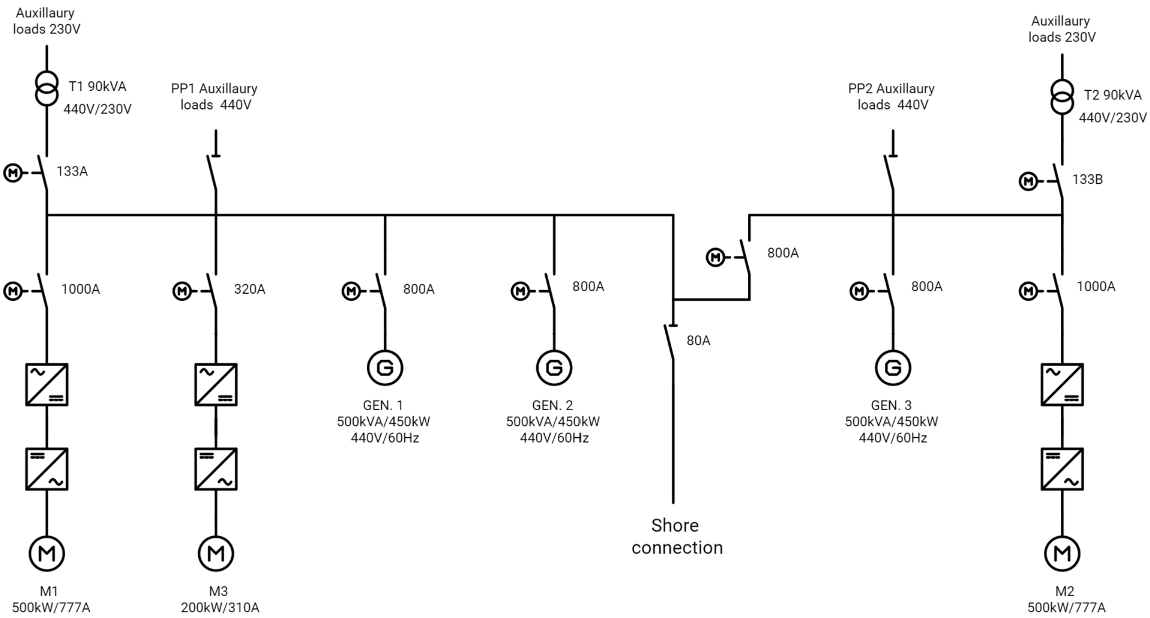


Figure 5.5: Single line diagram for RV Gunnerus.

The power demand calculations from subsection 2.2 were evaluated, revealing that the propulsion loads constitute the largest part of the total power demand in all modes. Even in DP mode, where the propulsion load is the lowest at 70 kW and the average total load demand is 90 kW, the propulsion load still accounts for 77.7% of the total average load demand.

When the BESS retrofit is evaluated from an electrical perspective, the vessel constraints must be assessed alongside the stakeholders' objectives. Available space is a limiting factor onboard RV Gunnerus. Using the dry provision room for battery space introduces some constraints, as discussed in (section 4.3.1). The FLEXSHIP project has required that RV Gunnerus be able to operate fully electrically. This requirement implies that the battery must supply both the auxiliary and propulsion loads. Another factor that differentiates the various options is their redundancy level. While FLEXSHIP has not specified redundancy as a requirement, the retrofit should at least maintain the existing level of redundancy. Additionally, the crew has outlined the minimum redundancy needed during DP and harbor maneuvering (Table 2.3).

From a general perspective, integrating a battery directly into the main switchboard with a DC-AC converter, as shown in Figure 5.1, is the most straightforward option. This approach would require the least amount of changes and new equipment. The installation of an AFE capable of converting around 1100 kW would be necessary to enable the battery to supply the total power demand with a full propulsion load.

Currently, a challenge onboard RV Gunnerus is the voltage fluctuations on the main switchboard caused by the VSDs. These fluctuations may pose difficulties for the battery in delivering power to the main switchboard through the AFE. This issue will be further elaborated in (subsection 5.2).

Hybrid grid 1, shown in Figure 5.3, would require the replacement of the two existing diode rectifiers in the VSDs of the propulsion, with AFEs. These rectifiers must handle at least 500 kW each to fully utilize the potential in the trusters. The AFEs are necessary to enable the batteries to supply the main switchboard in fully electric mode. However, when evaluating the fully electric mode with this configuration, it is observed that only the auxiliary loads of around 20 kW would flow from the battery to the main switchboard. This indicates that the rectifiers would only be working at about 4% of their capacity in electric mode. This brings forward the suggestion for retaining the diode rectifiers and adding a smaller AFE with a capacity of around 20 kW, as suggested in Figure 5.4. This option would require the additional installation of components, however will be a cheaper installation as you would only need to buy one AFE with a rated capacity of about 20 kW instead of two at 500 kW.

When comparing the three options, it is observed that hybrid grid 1 and 2 have fewer conversion stages, indicating better efficiency. It is noted that all options introduce a higher level of redundancy in normal hybrid operation compared to today's solution. When operating fully electric, the AC grid and the hybrid grid 2 present a vulnerability where the main switchboard is supplied by one AFE. In contrast, hybrid grid 1 has the power supplied to the main switchboard through two independent AFEs. Hybrid grids 1 and 2 have a higher redundancy as the main propulsion can receive power independently from the main switchboard.

5.2 Power quality

The Institute of Electrical and Electronics Engineers (IEEE) has defined the term power quality (PQ) to a wide variety of electromagnetic phenomena that characterize the voltage and current at a given time and a given location on the power system [55]. With this definition, PQ is the result of the interaction between different elements, including generation, distribution, and the use of electrical energy across the ship power grid. These elements ultimately influence the power grid of the vessel, and its overall functionality and safety. This approach to understanding PQ underlines the importance of ensuring that PQ is evaluated throughout the retrofit process.

Electrical equipment cannot be operated effectively if it is supplied with electrical energy of poor quality. As a result, both the reliability and operational safety of the systems are negatively impacted. Despite their other advantages, the usage of power converters harms power quality. In particular, voltage and current distortions are observed, sometimes necessitating the installation of filters in ship power systems [56].

Ship power grids, being isolated power distribution networks, face several challenges. These include the constraints of the power plant, characterized by subsystems operating at various voltage and frequency levels, and a limited number of energy sources. Additionally, the significant scale of certain power demands in relation to the total capacity of the installed power sources will influence the PQ. This becomes apparent on ships with electric propulsion, as these components will constitute a large part of the power requirement. Moreover, the complexity is increased by the parallel connection of multiple generators [57]. Thus, when retrofitting the power grid for ships, it becomes necessary to evaluate the PQ [58].

The primary concerns regarding PQ in ships are; voltage and frequency fluctuations, transient disturbances and voltage notching, harmonic and interharmonic distortion, and voltage imbalance [57].

Voltage and frequency fluctuations

The sources of voltage and frequency fluctuations can be attributed to the limited number of energy sources available on a vessel. The substantial scale of certain power demands, such as propulsion, cranes, thrusters, etc., along with their associated on/off switching, contributes to increased voltage and frequency fluctuations. Furthermore, the complexity of onboard installations, which include subsystems operating at different voltage and frequency levels, generators of varying sizes, prime movers, and control systems, complicates the management of these magnitudes. Figure 5.6 shows an example of a voltage fluctuation recorded during the switching of a large electric motor and an example of frequency fluctuation during a ship maneuvering [59].

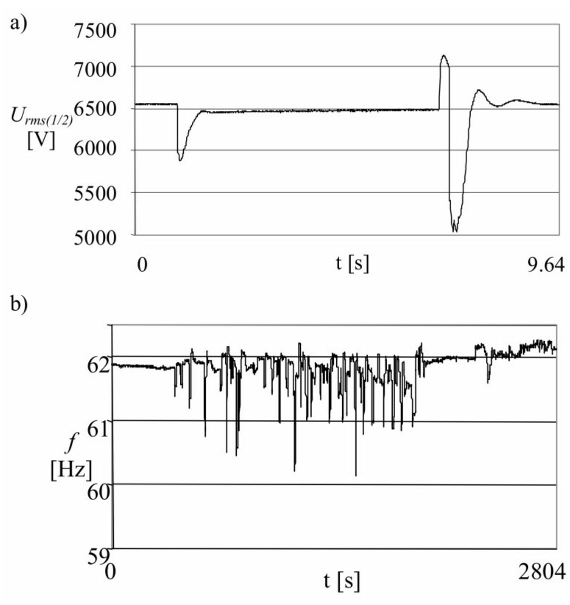


Figure 5.6: Visualisation of (a) voltage fluctuations and (b) frequency fluctuations [59].

To mitigate the impact of power quality disturbances, classification societies have established international marine standards that set boundaries for voltage and frequency fluctuations in ships' electrical systems. According to RINA Rules Part C, Chapter 2, Section 2, 2.1-2.2, these fluctuations must be constrained to the values shown in Table 5.1. Furthermore, Table 5.2 presents the requirements for systems that are connected to the battery depending on their function and requirements for operation during charging.

Table 5.1: Voltage and frequency variation limits for AC distribution systems from RINA.

Quantity in operation	**Variations**	
	Continuous	**Transient**
Voltage	±6%	±20% (recovery time: 1.5 s)
Frequency	±5%	±10% (recovery time: 5 s)

Table 5.2: Voltage variations for battery systems from RINA.

System	Variations
Components connected to the battery during charging*	+30%, -25%
Components not connected to the battery during charging	+20%, -25%

*Different voltage variations as determined by the charging/ discharging characteristics, including ripple voltage from the charging device, may be considered.

Transient disturbances and voltage notching

Transient disturbances are defined by IEEE as “pertaining to or designating a phenomenon or a quantity that varies between two consecutive steady states during a time interval that is short compared to the time scale of interest” [55]. Identifying transient disturbances is a significant challenge because of their short-lived occurrence, often less than the duration of one fundamental period, coupled with the presence of high-frequency components. This scenario requires the use of high sampling rates and real-time analysis. The creation of real-time detection and analysis methods and instruments is crucial for power quality evaluation, aiming to prevent negative effects on the electrical equipment aboard ships.

Transients in ship power systems usually result from the switching, on or off, of substantial power loads or due to variable loads. An example of such a transient disturbance in the voltage waveform within a 400 V subsystem of an all-electric ship is illustrated in Figure 5.7 [60].

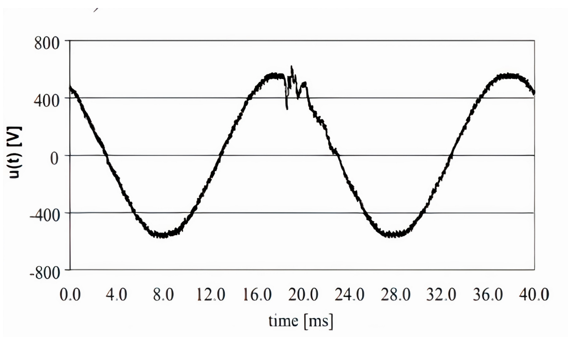


Figure 5.7: Transient disturbance in voltage waveform [60].

Voltage notching is a form of periodic waveform distortion, generated through the standard functioning of power electronic converters, which are widely utilized within ship power system grids, particularly in vessels fitted with electric propulsion systems [57]. Voltage notches occur when the current transitions from one phase to another within a power converter, leading to a temporary short circuit between two phases during this switch. The intensity of the notch depends on the inductance of the source between the converter and the monitoring point [57]. Figure 5.8 shows an example of voltage notches induced in a voltage waveform due to the operation of a six-pulse converter.

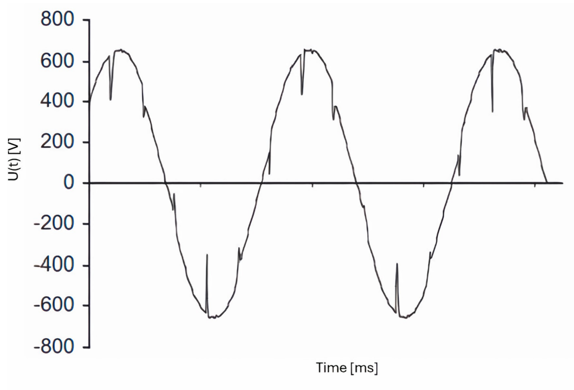


Figure 5.8: Voltage notching produced by a six-pulse converter [57].

Voltage notching is a type of PQ disturbance that occupies a middle ground between transient disturbances and harmonic distortion [57]. Because notching happens continuously and periodically, it can be analyzed using voltage harmonic distortion techniques. However, the frequency of the components involved in notching is often so high that traditional harmonic measurement tools cannot effectively characterize them.

International marine standards and marine classification societies' guidelines lack a standardized approach for detecting and analyzing both transient disturbances and voltage notching. Various methods for addressing transient disturbances are proposed in the literature, encompassing both time-domain and frequency-domain analyses. The application of the discrete wavelet transform on voltage samples, specifically analyzing the magnitude of the high-frequency coefficients, is proposed in [59]. Regarding voltage notching, the IEEE Std 519:2014 [61] provides a framework for characterizing voltage notching and sets limits for commutation notches and the total harmonic distortion (THD) factor. However, it does not specify any particular measurement method.

Harmonic distortion

When the load connected in a network is nonlinear, meaning it does not draw sinusoidal currents, the sinusoidal voltages can be distorted by the load currents. As these loads flow through the power system impedances, distortion is produced in the voltage waveform, ultimately affecting the entire power system. This deviation from the ideal sinusoidal waveform of voltage or current is referred to as harmonic distortion. This is typically caused by power converters, such as main propulsion, thrusters, compressors, and pumps. The growing usage of VSD to control the main propulsion also affects the harmonics of the system [57].

Another cause of the widespread use of power converters in ship power system networks is the high-frequency distortion and a high magnitude of interharmonic distortion in voltage and current waveforms, which are higher than those existing in inland power networks [57]. Interharmonics are frequency components that are not an integer multiple of the power system frequency [57]. In the case of ship power system networks, these interharmonic components can encompass the entire frequency spectrum and significantly deteriorate the voltage and current waveforms, affecting the entire power system, illustrated in Figure 5.9.

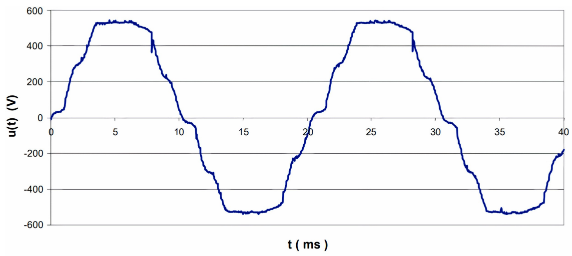


Figure 5.9: Voltage waveform with harmonic distortion caused by bow thruster [62].

The THD is a measure of the total content of harmonic components in a measured current, THD(i), or voltage, THD(u). Given in Equation 15 and Equation 16 [18].

$$\mathrm{THD}(i) = 100\% \times \frac{\sqrt{\sum_{h=2}^{\infty} i_h^2}}{i_1} \tag{15}$$

$$\mathrm{THD}(u) = 100\% \times \frac{\sqrt{\sum_{h=2}^{\infty} u_h^2}}{u_1} \tag{16}$$

In this context, $u_{(i)}$, $i_{(i)}$ represent the root mean square (RMS) value of voltage and current and is the 1^{th} harmonic of the voltage or current. This represents the fundamental value, the *clean* signal. h is the characteristic component, which means the parts of the measured signal that are not fundamental. These undesired signals are then calculated as a RMS value. The THD represents the percentage of unwanted signals, compared to desired signals.

Regarding harmonic distortion, the classification society RINA has established guidelines for different system configurations in Rules for the Classification of Ships Prt C, Ch 2, Sec 2:

For components intended for systems without substantially converter loads and supplied by synchronous generators:

- the total voltage harmonic distortion does not exceed 5%
- and the single harmonic does not exceed 3% of the nominal voltage.

For systems powered by static converters or where the converter load is predominant, the criteria adjust:

- individual harmonics are capped at 5% of the nominal voltage up to the 15th harmonic of the nominal frequency, decreasing to 1% by the 100th harmonic,
- the THD not exceeding 10%.

In the marine industry, a variety of solutions including active and passive filters, multi-pulse drive systems, and AFE drives, among others, have been employed for harmonic compensation in ships to adhere to the stringent limits set by classification societies. These technologies play a crucial role in mitigating harmonic distortions, ensuring that vessels meet the necessary standards for electrical power quality [57].

Voltage imbalance

In a polyphase system, the International Electrotechnical Commission (IEC) defines voltage imbalance as a condition in which the RMS values of the line voltages or the phase angles between consecutive line voltages are not all equal [63]. Voltage imbalance in power systems may arise from various factors, including asymmetrical impedances in distribution lines, unbalance among three-phase loads, differences in transformer winding impedances, the configurations of open Wye and open delta transformer banks, and the uneven distribution of single-phase loads. The ideal state of perfectly balanced three-phase voltages is seldom achieved, largely because of the constant engagement and disengagement of both single and three-phase loads within the network [64].

Among the equipment most susceptible to voltage imbalance are three-phase induction machines, power electronic converters, and drives. The adverse impact on induction motors is particularly notable, even minor discrepancies in three-phase voltages can lead to significant imbalances in phase currents. These imbalances amplify the heating effect and losses, consequently diminishing both the efficiency and longevity of the motor [57].

There are no class society requirements for voltage imbalance. However, according to National Electrical Manufacturers Association (NEMA) 3.5% of voltage imbalance can result in 25% added heating in different types of induction motors [65]. According to the IEEE, it is advised to address and rectify any instances where voltage imbalance exceeds 2%, to prevent the underlying issues from escalating. When the imbalance surpasses 5%, it is typically a situation in which one phase in a three-phase circuit becomes inactive or loses power. To safeguard three-phase motors against the negative consequences of such conditions, the implementation of phase monitors is frequently recommended [55].

5.2.1 Use case results: Power quality

When assessing the power quality from a retrofit perspective onboard RV Gunnerus, it is important to begin by evaluating the existing conditions. In 2015 RV Gunnerus was retrofitted with two permanent magnet azimuth thrusters. This included rebuilding the existing propulsion and retrofitting the power grid onboard with two azimuth thrusters.

The installed thrusters are controlled with VSDs. The VSD regulates the speed and torque of an AC motor by modulating its input frequency and voltage. In the first part of the VSD the ship power grid is connected to a passive 6-pulse diode rectifier that changes the fixed grid frequency alternating current, into DC current. In the second stage, often referred to as the DC-link, the DC circuit contains a capacitor used for filtering the DC power output from the previous step which contains voltage ripples. The DC power is inverted back to a pulsating AC voltage in the last part of the VSD. The switching rate is controlled to vary the frequency and voltage of the simulated AC that is applied to the thrusters.

In the case of RV Gunnerus the voltage distortion in the system is primarily caused by the VSD converters (6-pulse diode rectifiers) in the VSD, which draw a non-linear current. For RV Gunnerus, this distortion significantly affected auxiliary equipment such as pumps and cranes. Although multiple solutions exist, a THD filter is installed with the onboard auxiliary loads for Gunnerus. While this setup protects the auxiliary loads, it does not improve the harmonic voltage distortion at the main switchboard.

From a retrofit perspective, power quality assessment is primarily done through modeling the system and subsequently through measurement techniques for further analysis [66]. To evaluate the potential for BESS integration on RV Gunnerus from an electrical perspective, it can be beneficial to summarize the restrictions:

- The diode rectifiers in the VSD introduce harmonic distortion to the main switchboard.
- This has been accounted for by installing THD filters on the auxiliary equipment.
- Solving the harmonic distortion with the THD filters has led to the acceptance that there is harmonic distortion in the system.

When evaluating the three proposed grids, it is visible that the AC grid, as illustrated in Figure 5.1, might be challenging due to the low power quality on the main switchboard. An unsymmetrical voltage on the AC side of the AFE can influence the operating region for the converter. The operating region is the region where the DC voltage is relatively stable, and outside of this region, the DC voltage may pulsate. With increasing AC unsymmetrical voltage, the operation region decreases [67]. The varying voltage of the battery depending on the SOC, then poses a significant challenge. To enable this configuration, one would need to implement measures to mitigate the total voltage distortion on the switchboard. However, this could quickly become extensive and costly compared to the other solutions.

The solution proposed in hybrid grid 1 would largely fix the current PQ problem because changing the two diode rectifiers in the VSDs to AFEs would remove the biggest source of the voltage distortion. After evaluating the influence of the THD from the VSD for the bow thruster, the installed THD filters might also be removed resulting in freeing up space onboard after the retrofit.

Hybrid grid 2 would potentially present the same challenge as in the AC grid, in terms of delivering power through the AFEs to a main switchboard with bad PQ. However, in this configuration, the AFEs will only deliver power to the main switchboard in the fully electric mode. When in fully electric mode the battery will supply both the auxiliary loads and the propulsion loads, and no power will run through the passive diode rectifiers.

5.3 Shore-to-ship connection

S2S is the electrical interface between the shore grid and the vessel's electrical grid. For a vessel with a BESS, the S2S serves two purposes, it supplies the hotel loads, i.e., "cold ironing", and charges the battery. The required infrastructure for the S2S is highly reliant on the energy size and e-rate of the battery, the operational pattern for the vessel, and the available power from shore. Furthermore, where and how to convert the AC shore grid to the DC battery voltage must be evaluated. In this section, these subjects will be presented, and lastly an evaluation of solutions feasible for the use case.

The capacity of the battery sets the boundary for the maximum required energy, in a case where the vessel arrives at the harbor with 0% and later wants to leave with 100%. The battery's e-rate states the maximum continuous charging power, and by establishing these values, the theoretical minimum charging time is set. However, as discussed earlier, the use of e-rate is not a precise value as the battery has a certain voltage range, and the actual limitation is in current not power. Furthermore, the battery can not be charged with the maximum current from 0% to 100% of the SOC. Charging a lithium-ion battery usually follows a constant-current constant-voltage (CC/CV) curve as illustrated in Figure 5.10 [68]. The values for I_{max}, V_{max}, CC, and CV are a trade-off regarding charging time and battery degradation. Higher max values result in faster charging and faster degradation. Evaluating battery size, rates, and charging profile gives the required time to fully charge the battery. The vessel's operational pattern sets the usual time at the harbor, which gives the potential charging time. If the time at the harbor is less than the calculated required time to fully charge the battery, the battery cannot be charged from 0% to 100%. An evaluation of the importance of this opportunity should be conducted, considering if extending the time at the harbor is feasible. The available power from shore is a significant factor for the S2S. If the required power exceeds the available power, a battery pack on shore should be considered. The shore battery would charge while the vessel is at sea and discharge to the vessel when it is at the harbor.

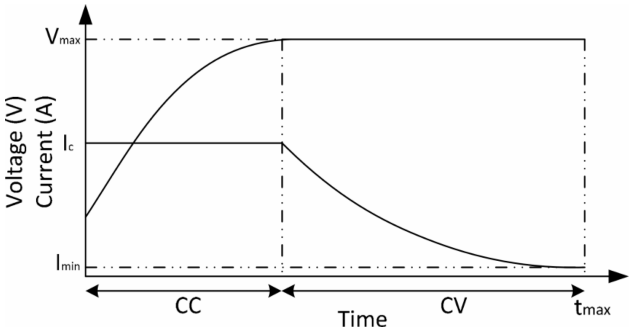


Figure 5.10: Typical charging profile [68].

There are several opportunities regarding the conversion from AC shore grid to DC battery. The first is to choose an AC or DC charging system, which means whether the S2S interface is AC or DC. Both solutions can be applied to both AC and DC onboard power systems. In [69], the different solutions were tested on ferries for different charging connections, including wiring. Karimi concluded that for a ferry with an AC propulsion system, a DC charging system was most effective, and for a DC propulsion system, both DC and AC were equally effective.

5.3.1 Use case results: Shore-to-ship connection

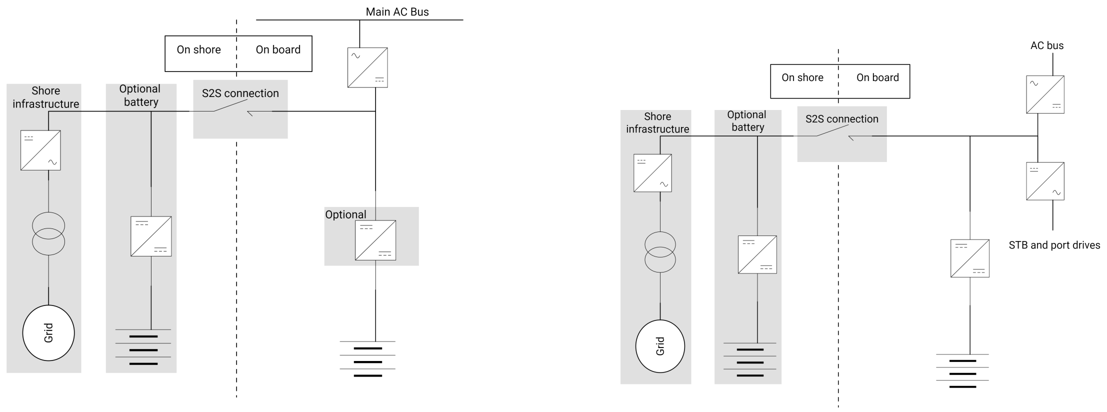
Based on AIS data, RV Gunnerus spends most of her time at the harbor, as shown in Table 2.2. A standard cruise day for RV Gunnerus is to leave the harbor at 8 am and return at 8 pm [28], which means there is usually about 12 hours of charging time. The battery size is set to 1 MWh, with an e-rate of 1.1, i.e., it would theoretically take 55 minutes to charge the battery with a charging power of 1100 kW. Fully charging the battery over 12 hours requires an average charging power of 83 kW.

According to *Trondheim Havn*, who operates the harbor used by RV Gunnerus, the capacity of the current shore supply is 55 kW however, it is possible to increase this to 350 kW [70]. The average charging time for RV Gunnerus is presented in Table 5.3. Note that the theoretical charging time is based on the maximum charging power over the whole charging cycle, and the actual time would be longer than presented.

Table 5.3: Charging times for RV Gunnerus.

Limiting factor	Maximum charging power [kW]	Theoretical charging time 0% to 100%
e-rate	1100	55 minutes
12 hours at harbor	83	12 h
Current available power	55	18 h
Potential available power	350	3 h

Regarding the S2S interface, a solution for AC grid 1 and the hybrid grids are presented in Figure 5.11a and Figure 5.11b, respectively. Note that the illustrated battery on shore is optional. Both solutions are based on a DC charging system, which means the least amount of components on board. However, this is not very common, so RV Gunnerus would not be able to charge in most other ports. As RV Gunnerus spends most of her night at Trondheim port, this is not considered a very critical capability.



(a) Charging topology for the AC grid.

(b) Charging topology for the hybrid grids.

Figure 5.11: Possible charging topologies for RV Gunnerus.

5.4 Power grid protection and selectivity

Protection and selectivity refer to protective relays and circuit breakers configured to ensure selective tripping and optimal protection of the power distribution system onboard. This configuration is important as continuity of service must be maintained, especially for critical loads affecting the ship's operational capabilities and safety. The principle of grid protection and selectivity can be divided into fault detection, location, and isolation [71]. When a failure of the ship power system occurs, the fault must be detected and isolated to obtain continuous power supply to non-faulty circuits, particularly those containing vital equipment.

Detection and location

To efficiently detect and locate a current fault, a proper strategy must be formulated. In each protection scheme, relays monitor measured data such as voltage and current, which are compared against predetermined safety thresholds. Trip signals are sent to the circuit breakers when these thresholds are exceeded. Protection schemes vary based on the types of measurements used, including voltage, current, power, and frequency, as well as the operating characteristics that define the trip thresholds.

Different strategies exist depending on the types of measurements used, such as exceeding a threshold, comparing with the mean average value, or employing adaptive techniques. In adaptive techniques, the calculated relay settings for various topologies are stored in a database and adjusted depending on the current ship grid configuration [72].

Once the fault has been detected, a strategy for disconnecting the faulty part of the grid must be applied. Effective coordination of primary and backup protection schemes is crucial for ensuring the reliability and safety of electrical systems. Primary protection serves as the first line of defense against the damaging effects of faults, while backup protection only occurs when the primary protection fails. The strategies for coordinating these protections can be categorized into two main approaches: time grading and communications [72].

Time grading uses a sequential and time-delayed approach for backup protection without relying on communication networks, leading to longer fault-clearing times. In contrast, communication-based schemes use a centralized control unit interconnected with measurement devices via communication networks, allowing for faster and more coordinated fault clearing, but they are more susceptible to communication failures and are generally more costly to implement.

Isolation

The main challenges regarding power grid protection related to DC circuit breakers are the lack of zero crossing and the danger of generating an arc with high fuse operating time [73]. To isolate a fault in the DC system, the current has to be forced to zero. Therefore, DC breakers use complicated mechanisms to extinguish large currents safely. Electromechanical circuit breakers were predominantly used to interrupt current flow by opening an electromechanical contact, utilizing substances such as air, vacuum, and sulfur hexafluoride (SF_6) for their high insulation strength. The current zero-crossing point is achieved through an oscillating current in a passive or active circuit, see Figure 5.12 A. Recently, solid-state circuit breakers (SSCB), which replaces the electromechanical contact with semiconductor switches, has been adopted. SSCBs provide the required open-circuit disconnecting capability, high current-carrying capacity, and high switching speed, see Figure 5.12 B. Additionally, hybrid DC circuit breakers, which combine SSCBs with traditional mechanical switches, have been developed, see Figure 5.12 C. However, SSCBs and hybrid breakers require control of the internal semiconductor switches, currently making them expensive and complex [21].

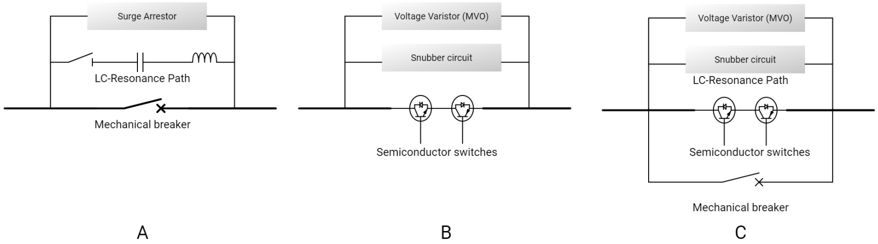


Figure 5.12: Simple schematics of typical DC circuit breakers. A is an electromechanical circuit breaker, B is a solid-state circuit breaker, and C is a hybrid circuit breaker. [21].

The short circuit breaking capacity for circuit breakers must be higher than the maximum expected short circuit current at the installation point. For circuit breakers with a brief delay, the maximum expected short circuit current at the moment the contact breaks at the installation point must be exceeded by the rated short time withstanding current. A long and short difference in the breaking time of each upper and lower protection device should be present in each short circuit protection device connected in series in the circuit. This condition is crucial for the protection of the marine power system. Furthermore, good dynamic and thermal stability should be ensured for components such as bus bars, disconnecting switches, terminals, and cables during the time required to clear the fault selectively [74].

Electrical requirements

Requirements given by RINA regarding the design of the ship power grids can be found in the RINA Rules Part C, Chapter 2. As this is from a retrofit perspective, most of these criteria have already been met. Given that the retrofit does not require rebuilding or changing large parts of the existing power grid. However, integrating a BESS as an energy source comes with some requirements.

RINA Rules Part C, Chapter 2, appendix 2 focuses on battery powered ships. The following paragraph aims to summarize the requirements related to the power grid integration of a BESS when retrofitting a ship.

Battery installations may replace diesel generators as the main source of electrical power, provided the battery's capacity is sufficient for the ship's intended operations. This limitation must be documented in the class certificate. When batteries serve as power storage for propulsion, dynamic positioning systems, or as part of the main electrical source, an EMS is required. Additionally, the system must ensure that the electrical supply for propulsion and steering is maintained or quickly restored in the event of a battery system failure. A risk assessment initiated during the design phase must evaluate risks, including gas development (toxic, corrosive), fire, and explosion risks, and outline measures for risk control and mitigation. Furthermore, the battery system's outgoing circuits must be protected against overload and short circuits using fuses or multipole circuit breakers with isolating capabilities. An emergency shutdown system capable of disconnecting the battery system in emergencies must be installed, along with a separate isolating device for maintenance, independent of the emergency shutdown system.

5.4.1 Use case results: Protection and selectivity

By evaluating the requirements for selectivity and protection in the use case, it can be observed that the two proposed battery integration methods, hybrid grid 1 Figure 5.3 and hybrid grid 2 Figure 5.4, includes keeping the existing AC power system and the main focus lies in safe integration of the battery and a DC-bus.

The proposed system is relatively small, and a time grading system appears to be viable. Although communication-based schemes are faster and allow for more coordinated fault clearing, they are more costly to implement. The time grading scheme offers a simple, sequential, and time-delayed approach for backup protection without relying on the communication network. This setup may allow for programming of the breakers in each VSD DC-link and the possibility to choose which one to be the primary breaker. Then the main switch from the battery can function as the backup protection if the primary protection fails.

The sizing of the DC circuit breakers needs to be evaluated concerning the voltage level and power for the proposed battery. As these properties are unknown at this stage in the process, it is not further investigated. To fulfill the requirements for selective protection, the battery needs to be disconnected from the DC-bus with circuit breakers for both the propulsion drives and the bow thruster. The battery also needs a circuit breaker and a disconnect switch to allow for maintenance of the battery system. An alternative configuration is given in Figure 5.13. In this case, DC breakers have been chosen for S1, S2, and S4. The battery is connected to the DC main link with a DC circuit breaker and disconnecting switch, see S3.1 and S3.2.

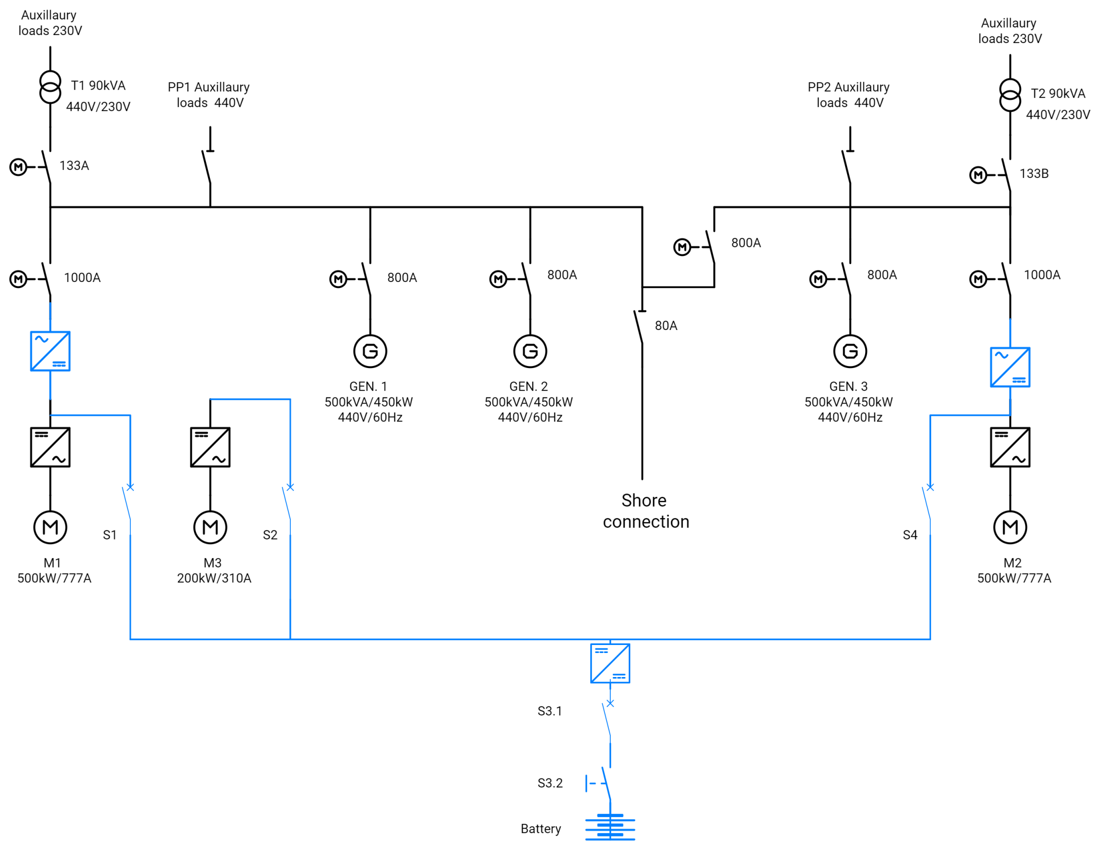


Figure 5.13: Hybrid grid 1 with selective protection breakers.

The short circuit breaking capacity for circuit breakers must be higher than the maximum expected short circuit current at the installation point. The rated power of the circuit breakers S1-S4 has to exceed the short circuit power of the battery. Furthermore, a breaking delay must be programmed for the main breaker from the battery. This will allow for a redundancy in the system. Finally, components such as bus bars, disconnecting switches, terminals, and cables should have a rated dynamic and thermal stability higher than they may experience during the time required to selectively clear the fault.

RINA requires an EMS to be integrated when installing a battery. This will be elaborated in section 6.

5.5 Discussion and recommendation for electrical integration

The three proposed grid options are possible from a general perspective, however, they pose some challenges to the existing network onboard RV Gunnerus. Although the AC grid, Figure 5.1, seems feasible and is a widely used way of implementing a BESS, it will pose some challenges regarding the PQ with voltage harmonic distortion being a challenge on the main switchboard for RV Gunnerus. Properly integrating a battery to the main switchboard, might require the introduction of THD propagating measures to improve the main switchboard PQ. This will make the option more complicated than initially assumed.

Hybrid grid 1 Figure 5.3, replacing the two diode rectifiers with AFEs would solve two problems, allowing for fully electric mode and improving the voltage harmonic distortion on the main switchboard. This option will be more expensive and require more modifications of the existing grid. The extent of the project and the objectives of the retrofit will need to be considered. It is clear that the AFEs have to be large enough to supply the propulsion loads. However, when they are used to supply power to the main switchboard, they will only need 4-5% of their rated capacity. This configuration might still be a good option for other ships with a higher hotel load. However, for RV Gunnerus, it makes more sense to go for hybrid grid 2 with the battery integrated to the DC-link of the VSDs, with a connection to the main switchboard with an AFE to supply the auxiliary loads in fully electric mode. This will not improve the PQ, but it will not worsen and is within the requirements as it is today.

From a PQ perspective, the unique characteristics of ship's electric power system render electric power quality a critical factor for the correct performance of the onboard electrical equipment. As evaluated in the grid design, it has to be accounted for by either having robust components that can handle it or by filtering it to make it better. The existing THD filters shield the auxiliary loads from distortion. By implementing the battery in the DC-link, the PQ on the AC main switchboard will not be an issue for the battery integration.

Evaluating the selective protection for the proposed DC-link presents some new requirements. Assessing the best possibilities shows that when working with a simple system like this, a time grading scheme with current monitoring is the best option.

In the next chapter, hybrid grid 1 and 2 will be further investigated and developed from a control perspective.

6 Control vessel integration

The last aspect of this preliminary design is the control integration. The pre-conceptual project analysis made the framework for retrofitting a hybrid vessel with a BESS. The concept design further helped evolve the understanding of the retrofit and showed the potential and possible savings. Evaluations conducted in the physical and electrical chapters of this preliminary design phase have a significant influence on the control aspect.

The control aspect of the BESS integration is vital to achieve the desired outcomes. The control system must coordinate the different energy sources according to the vessel's operational mode and the load demand. The overall goal is to achieve efficient energy distribution in a secure way. This section will first briefly explain the architecture components before it delves into the details necessary to establish proper energy and power management. This will be applied to the use case RV Gunnerus to suggest a possible rule-based control system, and as mentioned in subsection 1.3, the focus is on feasibility. The two suggested grid topologies from the electrical chapter, section 5, will be looked at separately.

6.1 Control system architecture

The architecture of a control system for a diesel-electric ship can be divided into three levels: primary, secondary, and tertiary layer, as shown in Figure 6.2. The primary layer is usually controlled by regulators such as automatic voltage regulator (AVR) and governors, and its primary concern is stability. The secondary layer consists of the PMS and controls the primary layer. The PMS gives the primary level set-points such as voltage and frequency, and start/stop signals. When a BESS is not installed, and the energy supply only comes from generators, the secondary layer is the highest level of the control system needed, as shown in Figure 6.1. When there is a BESS installed, there will also be a BMS in the secondary layer, and the system needs a tertiary layer that controls and optimizes the different suppliers, Figure 6.2. When retrofitting a ship with a BESS, there will be changes in the secondary and tertiary levels, the project will therefore focus on these levels. In a retrofit scenario, it can be beneficial to retain the existing PMS, which has demonstrated reliable performance, and develop the new control architecture to ensure its continued effective operation. However, this may be challenging in some cases, necessitating the development of the control architecture from scratch.

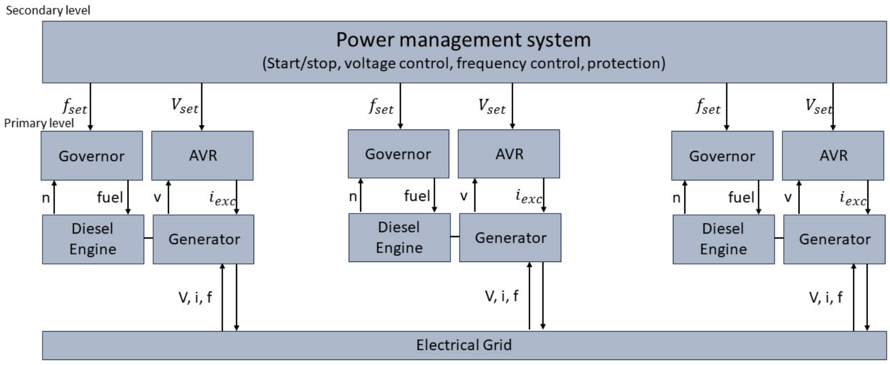


Figure 6.1: Control architecture without BESS, based on [75].

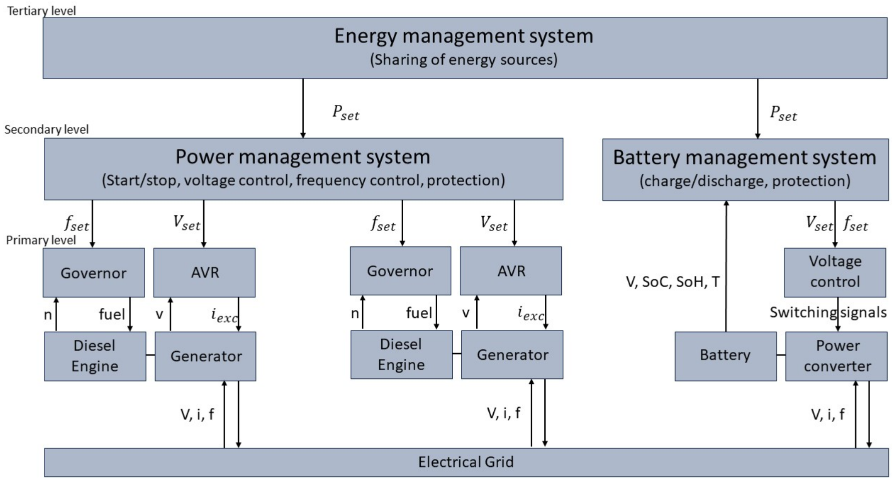


Figure 6.2: Control architecture with BESS, based on [75].

Energy management system: The current understanding of an EMS is a computer program that monitors and controls every power flow in an optimal way, as defined by the program. The EMS does not directly control the power flow; it sends desired set points, such as power or current, to the PMS, which executes the desired set point if possible.

Power Management System: The PMS is responsible for the secure control of the system, with its main objective being to ensure that sufficient power is always available. In cases where only generators serve as energy sources, the PMS securely distributes the load, thereby protecting the system from blackouts. If a blackout occurs, the PMS restarts the system securely and efficiently. When an EMS is present in the architecture, the PMS receives the desired set points from the EMS and continuously strives to achieve these values within its constraints.

Battery Management System: The BMS primarily acts as a monitoring component rather than a controlling one and functions the same way regardless of the operational mode.

However, as batteries become more commercialized, [76] suggests expanding the BMS into a more multi-functional component is preferable. While multi-functional BMS represents a state-of-the-art approach, this thesis will focus on a monitoring BMS. Typical data monitored and calculated by the BMS include cell temperature, cell voltage, current, SOC, and SOH. The class societies also specify the minimum requirements as mentioned in section 4.3. This thesis will not study the BMS further as it is more sensible to do later in the process when a battery manufacturer is selected. In the control architecture, the BMS will be seen as a component that gives "yes" or "no" to the EMS if the battery is available, in addition to providing the battery SOC. If the BMS detects that a value is outside its limit, it will simply report to the EMS that it is not possible to use the battery.

The presented interface between the tertiary- and secondary-level control components is not a clear definition. Different architectures define the interface slightly differently, some even combine them as a power/energy management system (PMS/EMS), [23]. The importance is not in the interface between the control components but in the functionality and reliability of the whole system.

6.2 Desired outcomes

The desired outcome of the control architecture for the BESS retrofit integration is a reliable and safe power distribution that increases the vessel performance and decreases fuel consumption. In subsection 2.2, it was defined that RV Gunnerus has the following operational modes: *at harbor, harbor maneuvering, transit, and DP*. In each mode, the vessel can operate its power system by combining its power sources in various ways. Within each operational mode, the use of the battery can also vary, depending on whether it is for *enhanced dynamic performance*, *strategic loading*, operating *fully electric*, or serving only as *spinning reserve*. The control system must operate as intended in all of the vessel's operational modes and give the operators flexibility in how they want to use the different power sources. Additionally, it must be robust by making it impossible for the operator to cause a blackout situation inadvertently.

No battery is a mode without the BESS. It should be possible to disconnect the BESS and operate the vessel as a diesel-electric vessel in the same way as before the retrofit.

Fully electric is a mode where the BESS supplies all the power demand. For this to be achieved, the BESS needs to be able to deliver power to all consumers. The BESS is connected to the DC-link of each VSD and can effectively supply the propulsion loads. However, for the BESS to deliver power to the auxiliary loads, power must be able to flow from the DC-bus to the main switchboard.

Spinning reserve is a mode with a surplus of available power, meaning that a rapid change in power demand or power supply should not lead to a blackout but be handled by the spinning reserve. The class societies allow BESS to function as spinning reserves [35]. If a BESS is to function as a spinning reserve in a DP operation, it is vital that the BESS is large enough and can supply the necessary power demand almost instantaneously. If a diesel generator has a malfunction that leads to a shutdown, the BESS must be able to handle the power demand. Simply because the vessel has a BESS onboard does not mean this is achieved. The control architecture must be built in a manner that can respond fast enough. This is particularly useful when the vessel is in DP mode due to the possibility of shutting down one of the diesel generators and still having enough redundancy, resulting in lower fuel consumption.

Strategic Loading is to operate the BESS in a way that enables the diesel generators to operate in fuel-optimal regions by either charging or discharging when not in an optimal region, with regards to SFC. This means that when the diesel generator runs close to optimal SFC, the BESS is not in use. If the diesel generator is running in a non-optimal region, resulting in a high SFC, the BESS can start charging, if possible, concerning the BESS SOC. Alternatively, a generator can be shut down and let the BESS discharge. This increases or decreases the total generator load to an optimal region, resulting in a more beneficial SFC. When to charge the BESS and when to discharge the BESS are essential parameters to consider in the control architecture concerning strategic loading.

Enhanced dynamic performance can be achieved by letting the BESS supply the necessary power in a load change, and the diesel generator can gradually be increased. If the load rapidly decreases, the battery can charge, and the diesel generator can decrease slowly. The control system decides how fast the diesel generator should respond, and the BESS should be able to handle the fast changes. This has proven to be easier with varying DC-bus voltage than with a fixed DC-bus voltage [46]. The vital part for the BESS to achieve this function is the electrical components in the system and the parameters the control architecture uses. *Enhanced dynamic performance* is not a mode in itself but can be achieved in both the *strategic loading* mode and the *spinning reserve* mode.

6.3 Energy management system

To begin the development of the EMS for RV Gunnerus, an understanding of the desired outcomes of the BESS utilization concerning the vessel's operational modes is required. Before delving deeper into the control architecture's details, an overview of how the EMS can function should be made. In Figure 6.3, a flow chart with four BESS utilization options is controlled by the operator. The control parameters are displayed in the flow chart for the *fully electric* mode and the *no battery* mode. The control becomes more complex for the *strategic loading* mode and the *spinning reserve* mode, as shown in Figure 6.4 and Figure 6.5.

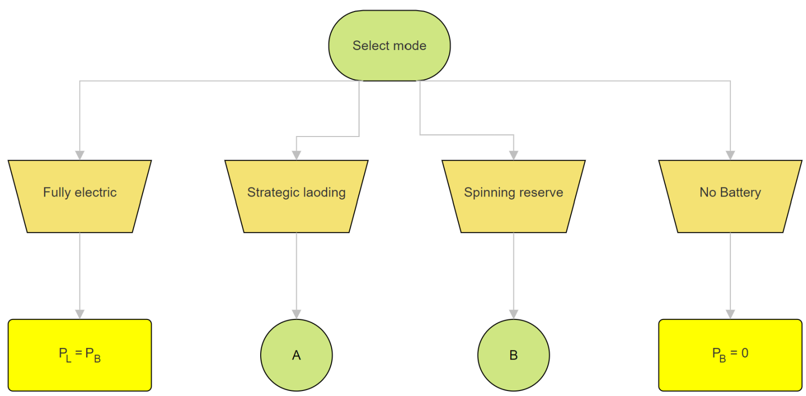


Figure 6.3: Flowchart overview of the four modes, with simple control parameters for *fully electric* and *no battery* mode.

With this configuration, the operator must decide how to use the battery by selecting one of the four modes. In the *fully electric* mode, the power load (P_L) is required to be equal to the power from the battery (P_B). This means that the battery supplies all necessary power loads. In the *no battery* mode, P_B is set to zero. This results in no power supply from the BESS, necessitating the vessel's operation solely with the diesel generators as the power supply.

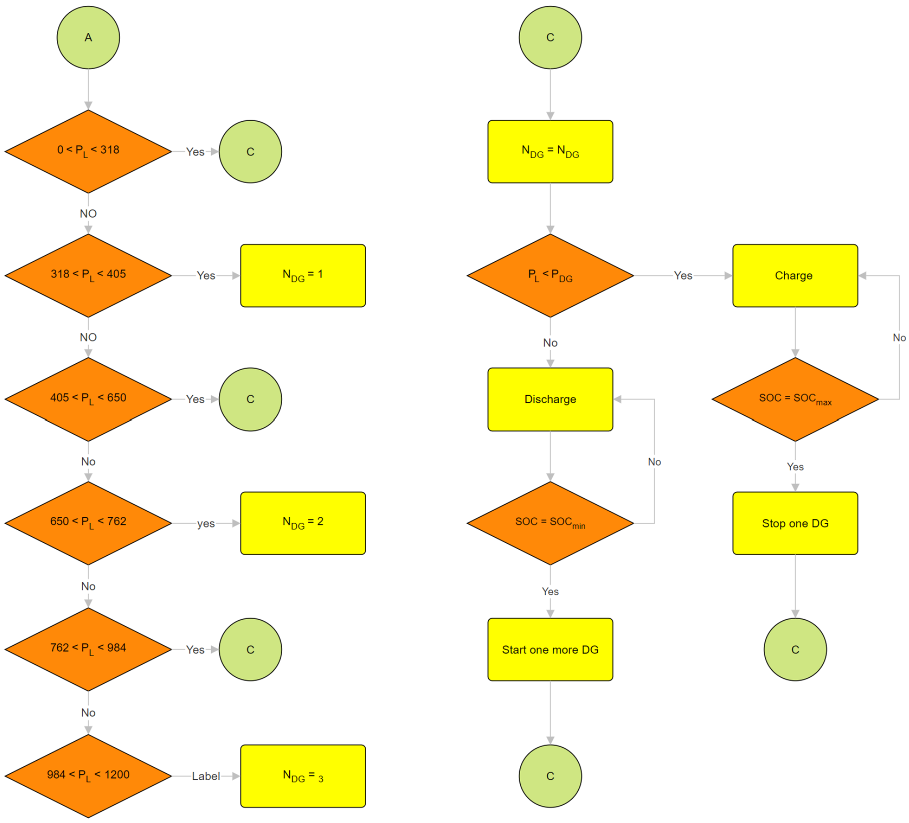


Figure 6.4: Flowchart of a possible *strategic loading* mode.

In the *strategic loading* mode, the EMS must state when it is beneficial to use only the diesel generators and when to charge or discharge the battery. The proposed flow chart in Figure 6.4 is based on the vessel's SFC for different loads, as calculated in Figure 3.6, using actual fuel consumption data and generator load data. The calculations on when to avoid using the battery, charge it, or discharge it can be seen in Figure 3.7b. The P_L values are in kW, and N_{DG} refers to the number of diesel generators running.

In certain load demands, the diesel generators operate close to optimal conditions, and due to low SFC, it is not beneficial to charge or discharge the battery due to power conversion losses. The BESS can still provide *enhanced dynamic performance* with the appropriate control architecture. When the diesel generators are not running close to ideal loads, it is necessary to decide if the battery should charge or discharge, as indicated by the "C" in the flow chart.

When the vessel changes its load demand to a specific load range, the EMS should maintain the same number of running diesel generators to avoid unnecessary starts and stops. Then, it must check if the P_L is less than what the running diesel generator(s) can deliver (P_{DG}) to decide whether to charge or discharge the battery. When the BESS reaches SOC_{max}, one diesel generator should stop, and when it reaches SOC_{min}, one diesel generator should start.

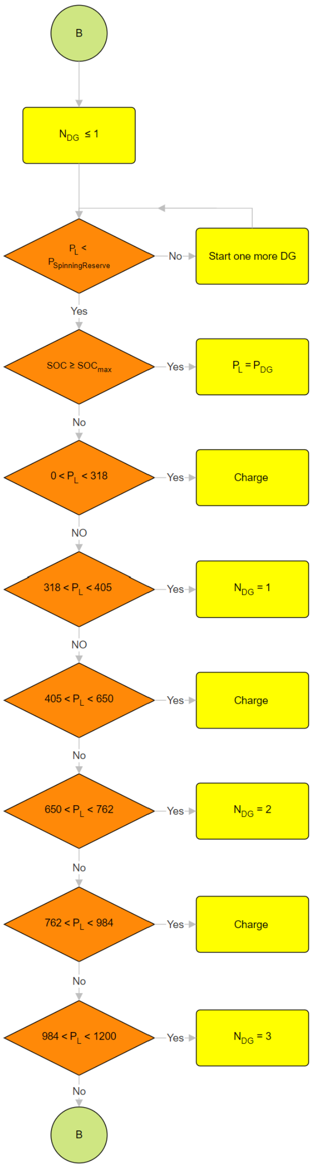


Figure 6.5: Overview of the *spinning reserve* mode.

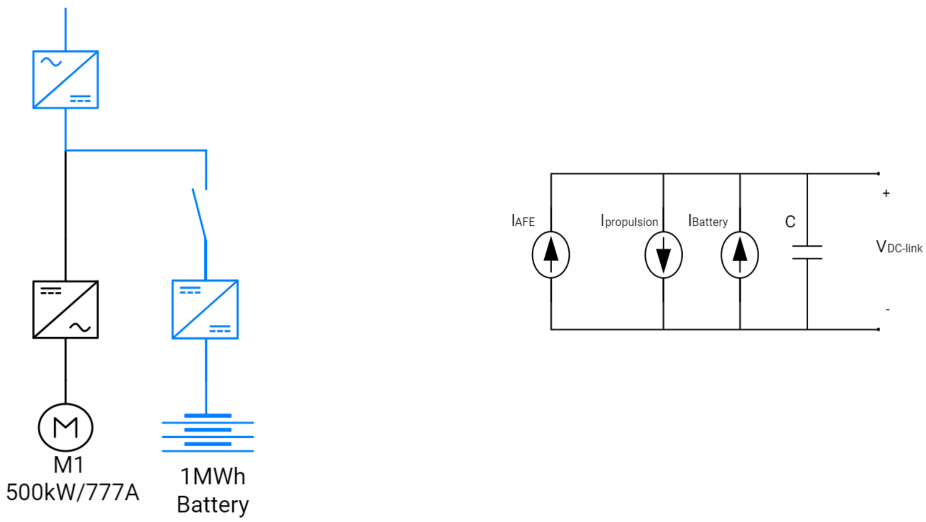
In the *spinning reserve* mode, the primary concern is to keep two available power sources running, ensuring that one power source can deliver the entire power demand. This setup ensures continuous operation if one power source fails. The proposed flow chart in Figure 6.5 begins by ensuring that at least one diesel generator is running. It then checks that the power load (P_L) is less than the required available power ($P_{SpinningReserve}$). If this is not the case, an additional diesel generator should be started.

If the battery SOC equals SOC_{max}, P_L should match P_{DG}, and the PMS will ensure this alignment. In different P_L ranges, the EMS will either charge the BESS or operate solely on the diesel generators. Discharging the battery is not considered beneficial since this mode prioritizes safety, and the load demands are generally relatively low. Nevertheless, the BESS can still achieve *enhanced dynamic performance* with the appropriate control architecture.

6.4 Power management system

The PMS controls the power flow of the power sources, ensuring that the necessary power is available and the system remains stable. This control can be achieved through various techniques and by managing components such as power converters, governors, and AVR. The PMS is also responsible for ensuring system safety by implementing shutdown criteria in critical situations. These emergency shutdown criteria must be set according to the robustness of the electrical components in use to prevent severe damage.

Development of the control system for BESS integration on RV Gunnerus will primarily focus on the control aspects necessary to achieve the desired outcomes of battery utilization. Since this is a retrofit project, the new control system will be designed to maintain the functionality of the existing PMS. The new system consists of a PMS for the new power electronic components and a new EMS. The PMS will be referred to as the DC PMS, focusing on controlling the battery utilization through the DC-bus. Evaluating the design of the DC PMS, it is necessary to investigate further the two integration methods proposed in subsection 5.5.

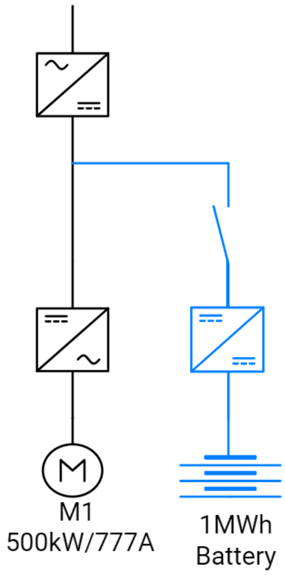


(a) Hybrid grid 1, DC-bus single line diagram.

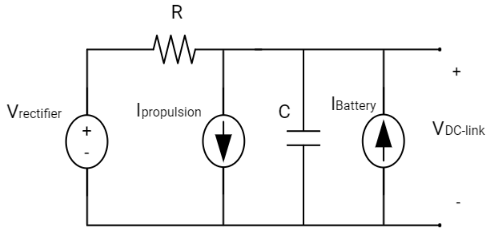
(b) Hybrid grid 1, DC-bus circuit diagram.

Figure 6.6: SLD and circuit diagram for hybrid grid 1.

In hybrid grid 1, the VSDs are connected to the main switchboard through AFEs. The AFEs are bidirectional and can be set to control current while converting power to the DC-bus or the main switchboard. The battery will be connected to the DC-bus through a controllable DC-DC converter. This configuration with DC-DC converter and AFE gives significantly more control options concerning the DC PMS design compared to hybrid grid 2. The control of the AFEs can be viewed as control of the generators because the AFEs will directly affect the main switchboard, which in terms affects the old PMS, controlling the generator's response. The strategy proposed for the DC PMS in this option will be to maintain a constant voltage on the DC-bus. This can be achieved by ensuring the DC-DC converter is dedicated to maintaining constant DC-bus voltage. The battery will then respond to swift load changes, and the AFEs can be controlled to more slowly follow the demand, enhancing dynamic performance. In Figure 6.6a, the DC-bus is illustrated with the components connected to it. This allows the PMS to ensure that the generators follow the load while the battery works for enhanced dynamic performance. The EMS can overwrite the generator supply to differ from the load if desired. The corresponding circuit diagram is sown in Figure 6.6b. The possible solutions for the DC PMS will be further elaborated in subsubsection 6.5.1.



(a) Hybrid grid 2, DC-bus single line diagram.



(b) Hybrid grid 2, DC-bus circuit diagram.

Figure 6.7: SLD and circuit diagram for hybrid grid 2.

In hybrid grid 2, the VSDs are connected to the main switchboard through passive diode rectifiers, as illustrated in Figure 5.4. The passive diode rectifiers are not possible to control, but they will be affected by the propulsion load and the voltage on the main switchboard, mainly controlled by the existing PMS. The BESS is connected to the DC-link in the VSD through a controllable DC-DC converter. To achieve the desired outcomes of the battery utilization in hybrid grid 2, it is necessary for the DC PMS to indirectly control the existing PMS and the generators by controlling the BESS usage through the DC-DC converter. In this option, there is also a small AFE connecting the DC-bus directly to the main switchboard. However, this component is only meant to supply the auxiliary loads when the vessel is running in *fully electric* mode and is not deemed capable of contributing to the control aspects of the other modes. The DC PMS responds swiftly to load changes, making the battery respond faster than the generators through the diode rectifiers. The battery slowly reduces its power supply so the generators can take the power demand to achieve enhanced dynamic performance. The EMS should work the same way as for hybrid grid 1, but in this case, it controls the DC PMS over the DC-DC converter. A representation of the connection between the battery and the DC-link can be seen in Figure 6.7a, with the corresponding circuit diagram in Figure 6.7b. The equivalent circuit diagram's resistance (R) represents the average DC voltage drop due to the commutation process. The DC current is not completely flat, there exists some ripple which causes the average DC voltage to drop with the current flowing through (I_d). The drop can be represented with $\frac{3}{\pi}\omega L_s I_d$ [77]. The possible solutions for hybrid grid 2 DC PMS will be further elaborated in subsubsection 6.5.2.

6.5 Use case results: Control integration

The system architecture for the two solutions is constructed differently. A graphical overview of hybrid grids 1 and 2 is illustrated in Figure 6.8 and Figure 6.9, respectively. Note that the blue components are new additions for the retrofit, while the orange components are existing ones.

For hybrid grid 1, the EMS directly controls the PMS for the AFEs. This approach allows the EMS to indirectly set desired values for both the battery and the generators. In hybrid grid 2, there is no control over the AC-DC converters. Instead, the EMS directly controls the PMS for the battery and indirectly controls the generators.

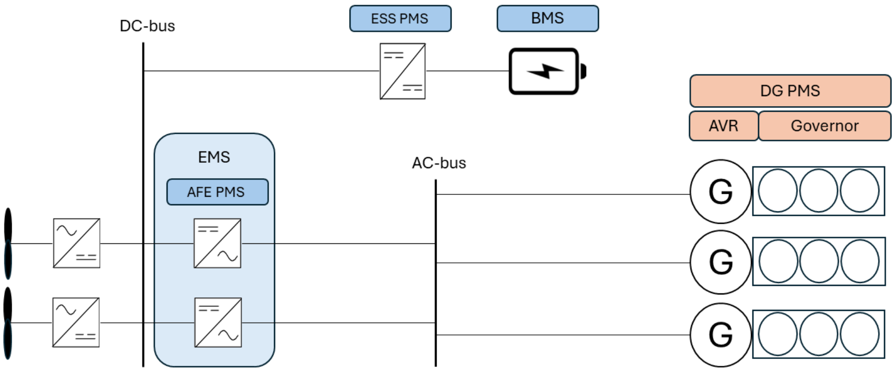


Figure 6.8: Graphical control architecture for hybrid grid 1.

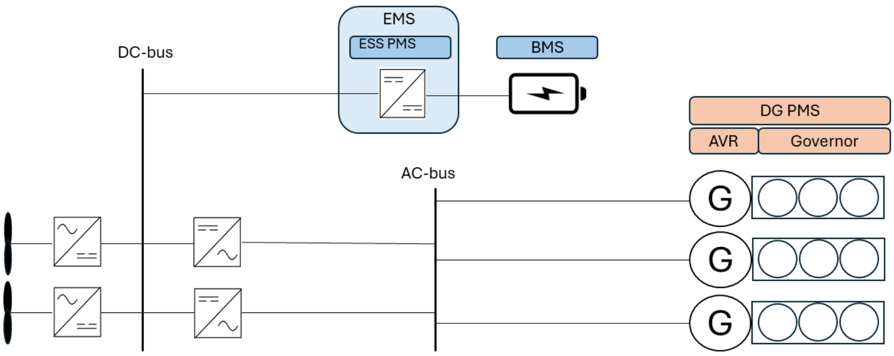


Figure 6.9: Graphical control architecture for hybrid grid 2.

The signal and power flows for both solutions, along with their interface with the existing control system, are presented in Figure 6.10 and Figure 6.11. Both cases are current-controlled. In hybrid grid 1, the desired AFE current ($I_{AFE_{set}}$) is signaled from the EMS to the AFE PMS. This can be considered a request from the EMS to the PMS. The PMS aims to meet this value and signals an AFE current reference ($I_{AFE_{ref}}$) to the AFE, which executes the power flow.

The BMS continuously monitors the battery and sends the SOC to the EMS, indicating whether the battery is ready to be utilized. The ESS PMS receives the battery status through the EMS. If the battery is ready, the ESS PMS aims to handle the difference between the demand and generator supply.

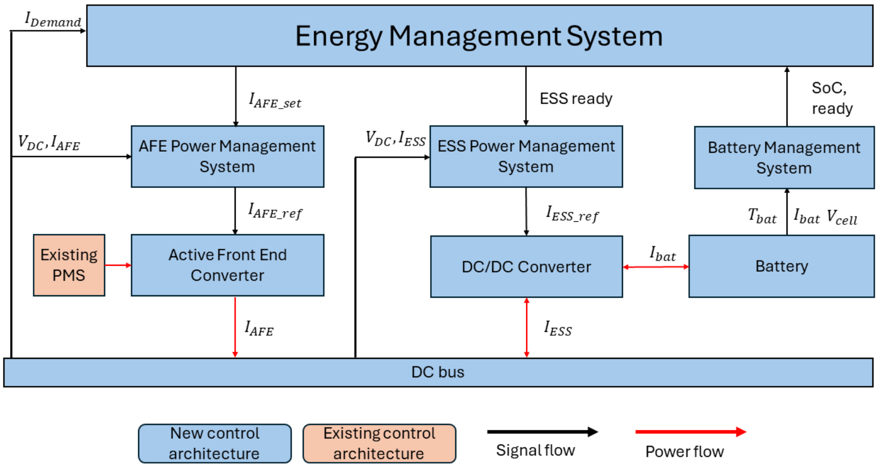


Figure 6.10: Control architecture for hybrid grid 1.

Hybrid grid 2 shares several similarities with hybrid grid 1, but also some differences. Firstly, the EMS sends a desired ESS current to the ESS PMS ($I_{ESS_{set}}$). The ESS PMS aims to meet this desire and sends a reference ESS current ($I_{ESS_{ref}}$) to the DC-DC converter, which executes the power flow. Furthermore, if the BMS states that the battery is not ready to be utilized, this information is handled by the EMS, and the desired current is then set to zero.

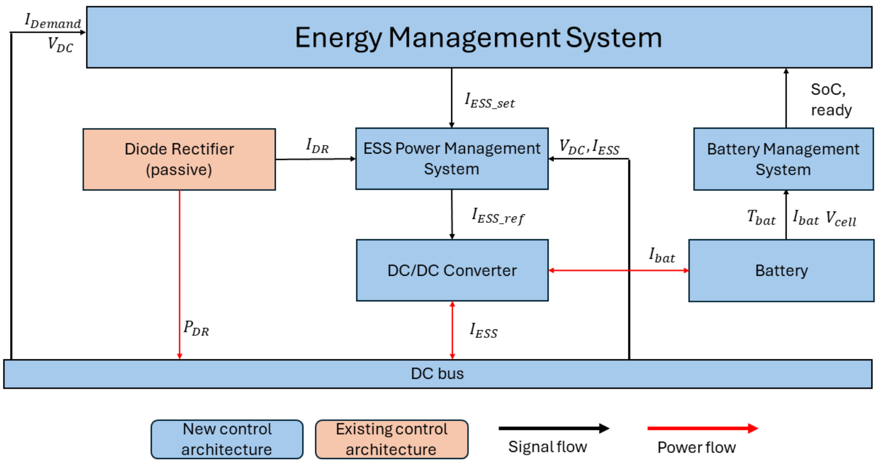


Figure 6.11: Control architecture for hybrid grid 2.

6.5.1 Simulation of hybrid grid 1

To test the feasibility of the solutions, it is necessary to simulate them. By running the two solutions on real load data, the difference in performance and potential savings can be visualized. This, and the next section, describes how the simulation model for both solutions is built up. The simulations for both options are limited to the DC side of the system, i.e., the DC-bus. The models are made in Simulink and simulated in continuous mode. For hybrid grid 1, the DC-bus and the PMS were provided by Marius Ulla Hatlehol, and this thesis has further developed the control system with a EMS and slightly adjusted the PMS. For hybrid grid 2, the DC-bus, PMS, and EMS have been developed, inspired by the work provided.

The propulsion system is represented by two current sources that supply negative current, indicating a demand for current. The battery, along with its DC-DC converter, is also modeled by a current source capable of supplying both positive and negative current. The AFEs are likewise represented by current sources. An overview of the DC-bus is shown in Figure 6.12.

The value MP_{Iref} denotes the main propulsion demand and can either be a predetermined value or a dynamic value derived from a load profile during an actual voyage. The SOC calculations compare the throughput of amperes to the total capacity in Ah, adjusted for the voltage difference between the battery and the DC-bus. While this estimation is simplified, it is adequate for this purpose.

The values for the DC-DC converter, ESS_{Iref}, and the AFEs, AFE_{Iref}, are specified by the PMS for each power converter. A complete table that explains and lists the values for the properties used in the simulation is provided in Table 6.2.

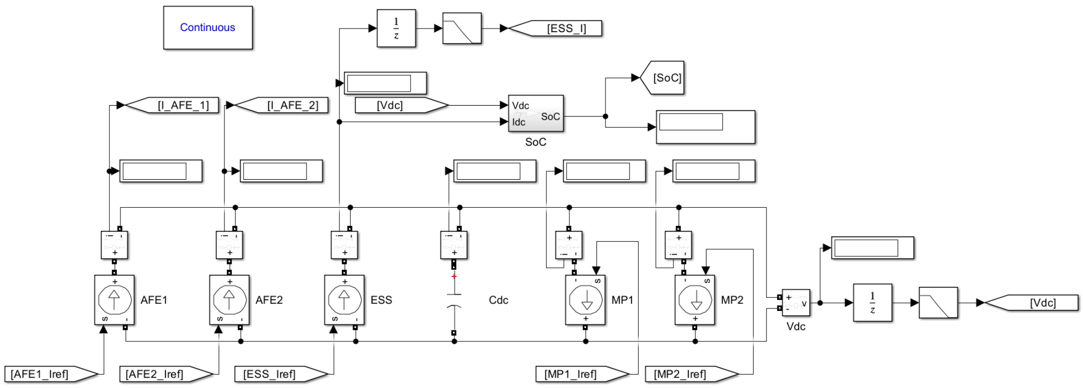


Figure 6.12: Overview of the DC-bus for hybrid grid 1.

The PMS for the DC-DC converter maintains the DC voltage at a constant value of 1000 V in this simulation. By doing so, the battery can quickly respond to sudden demand changes from the MP_{Iref}. An illustration of the ESS PMS is provided in Figure 6.13.

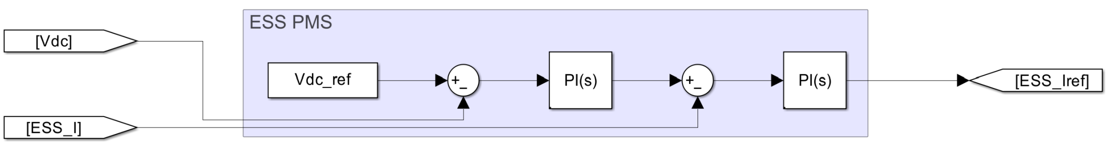


Figure 6.13: ESS PMS for hybrid grid 1.

The PMS for the AFEs receives input from the EMS regarding the desired current. Based on the DC voltage, the desired power from the EMS is compared to the actual output power from the AFE. The difference in power is converted to a voltage difference through a droop-setting. The actual power output from the AFEs is also converted using a droop-setting, but this setting is only 2.5% of the one used for the desired power output. This slows the reaction time for the AFEs, allowing the battery to manage sudden changes, while the generators gradually take over the power demand through the AFEs, achieving enhancing dynamic performance. By adjusting the desired current from the EMS, the power supplied by the generators can be controlled, with the battery handling the rest. The AFE PMS is illustrated in Figure 6.14.

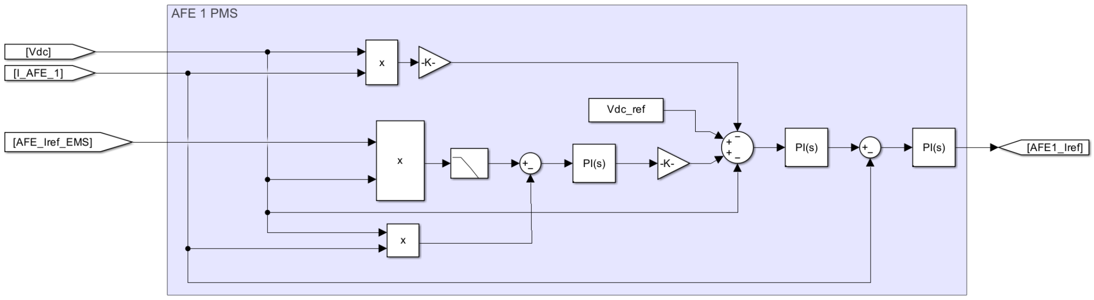


Figure 6.14: AFE PMS for hybrid grid 1.

The balance between the generators and the battery is determined by the EMS, and different operations require different settings, as described in subsection 6.2.

In fully electric mode, the EMS requests 0 amps from the AFEs. Although hotel load is not considered in this simulation, the desired current could be adjusted from zero to a negative hotel load if needed.

For strategic loading mode, two look-up tables are used, one for charging and one for discharging, shown by the blue and red lines in Figure 3.7b. The desired generator power is determined from these tables based on the power demand from the main propulsion. A toggle switch decides whether to follow the charging or discharging table. The switch always starts with discharging to use any available shore-charging energy. When the SOC reaches the lower limit, the switch changes to charging, continuing until the SOC reaches the upper limit. The EMS for strategic loading is illustrated in Figure 6.15.

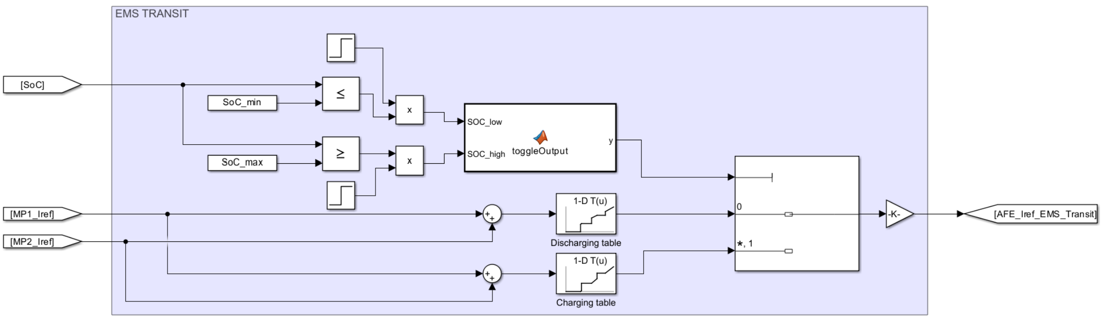


Figure 6.15: Strategic loading EMS for hybrid grid 1.

The EMS for spinning reserve mode prioritizes redundancy over fuel efficiency. Firstly, the available spinning reserve in the battery is calculated. This value is compared to a lower limit for operating with one generator and the battery. If the reserve is insufficient, an alarm is activated in the interface, warning the operator. The operator can then choose to start another generator or dismiss the alarm. Since redundancy is not a class-society requirement, the EMS does not automatically start another generator.

Furthermore, if the battery is not at its upper limit, the generator follows the same charging look-up table as in transit mode. When the battery reaches its upper limit, the generators meet the demand, and the battery serves solely as a spinning reserve.

A simple interface is created in Simulink to visualize the current operating mode. The interface includes two buttons: one to activate fully electric mode and another to activate spinning reserve mode. If neither button is pressed, the system runs in strategic loading mode. Additionally, a thrust actuator is included to adjust the power demand manually.

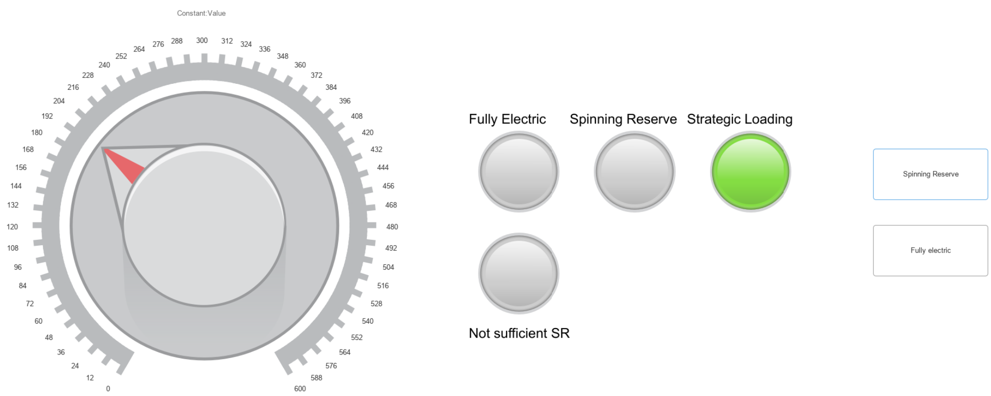


Figure 6.16: EMS interface for hybrid grid 1.

6.5.2 Simulation of hybrid grid 2

The DC-bus for hybrid grid 2 is illustrated in Figure 6.17. It resembles the DC-bus for grid 1 concerning main propulsion, the battery, and SOC calculations. However, this option replaces the AFEs with two voltage sources in series with a resistance. The voltage sources represent the diode rectifiers, and the resistance accounts for the average voltage drop due to the commutation process. This drop is modeled by the resistance, causing a voltage droop on the DC side.

The voltage from the diode rectifiers depends on three parameters: the AC voltage (V_{rms}), omega (ω), and the load current (I_{DR}). For these calculations, V_{rms} and ω are assumed to be constant. The DC voltage can be calculated using Equation 17. Given the constant V_{rms} and ω, the voltage varies only with the current through the diode rectifier (I_{DR}).

$$V_{DC} = V_{NL} - \frac{3}{\pi}\omega \cdot L_S \cdot I_{DR} \tag{17}$$

$$V_{NL} = \frac{3\sqrt{2}}{\pi}V_{rms} \tag{18}$$

To estimate the value L_S, the generator datasheet, Appendix F, is used. The relevant data is presented in Table 6.1. The base impedance (Z_B) can be found as illustrated in Equation 19. Where V_L is the line voltage, and S_L is the line apparent power.

Table 6.1: Generator data.

Description	Value	unit
Voltage	440	V
kVA base rating	520	kVA
x_d	2.85	p.u.

$$Z_B = \frac{V_L^2}{S_L} \tag{19}$$

The base inductance (L_B), is calculated as shown in Equation 20, where ω_B is the base angular frequency ($2\pi f$).

$$L_B = \frac{Z_B}{\omega_B} \tag{20}$$

In the per-unit (p.u.) system, the stator inductance (l_s) is the same as the stator reactance (x_s). However, the generator datasheet does not provide these values because the rotor is not cylindrical. Therefore, the worst-case reactance in the d-q plane (x_d) is used. Although this method is not entirely precise, it serves the intended purpose. The final calculation for the stator inductance in SI units (Henry) is provided in Equation 21.

$$L_S = L_B \cdot l_s = L_B \cdot x_s \approx L_B \cdot x_d \approx 2.815mH \tag{21}$$

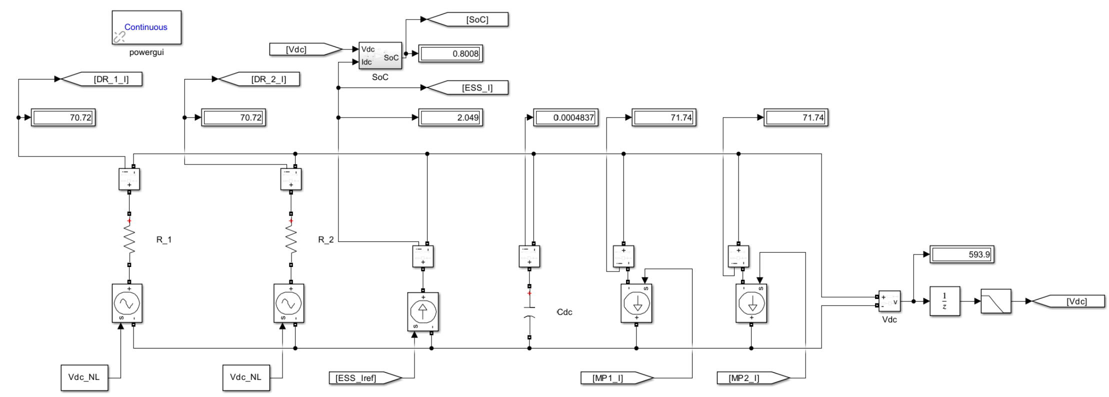


Figure 6.17: Overview of the DC-bus for hybrid grid 2.

The diode rectifiers have no PMS because they are passive and cannot be controlled. The only controllable element in this configuration is the power from the DC-DC converter connected to the battery. The PMS for the battery receives an input from the EMS called $I_{ref_{EMS}}$, representing the desired current from the generators, which can not be directly controlled. However, the PMS adjusts the ESS current, so that the diode rectifier current meets the desired value.

The desired power from the diode rectifiers sets the desired DC-bus voltage. This voltage is compared to the actual voltage, and the signal is processed through a PI regulator. The difference between the main propulsion current and the diode rectifier current is then filtered through a low pass filter and compared. This method achieves enhanced dynamic performance by allowing the battery to handle sudden power changes while the generators gradually adjusts their load.

Thus, the PMS ensures enhanced dynamic performance, and the EMS ensures the desired power sharing between the generators and the battery. The PMS for the ESS is illustrated in Figure 6.18.

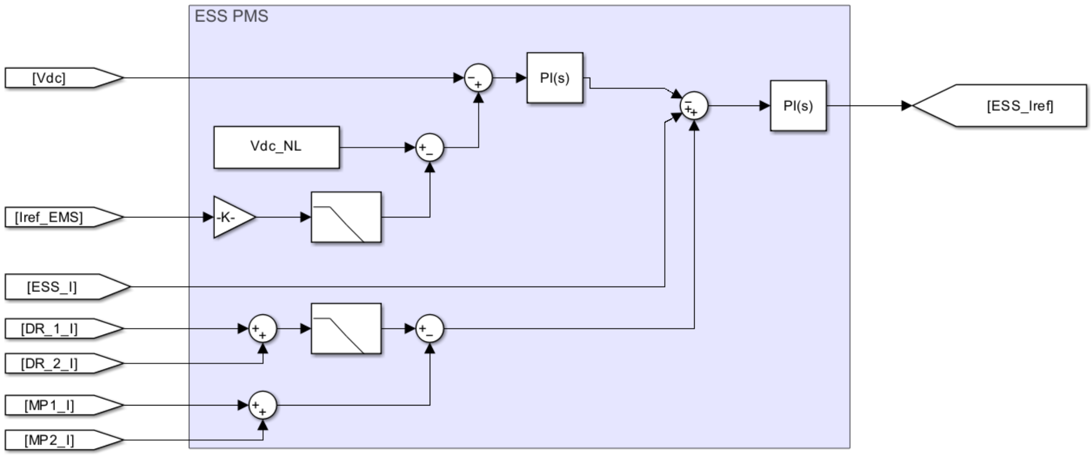


Figure 6.18: ESS PMS for hybrid grid 2.

The PMS for the battery relies on the desired power input from the generator. Therefore, the EMS designed for hybrid grid 1 can be reused for this option and is not further elaborated.

Table 6.2: Simulation properties.

General		
Nominal battery voltage	ESS_{VN}	800 V
Battery capacity	ESS_{Wh}	1 MWh
Battery capacity	ESS_{Ah}	1250 Ah
Lower limit SOC	SoC_{min}	20%
Upper limit SoC	SoC_{max}	80%
Minimum spinning reserve	$SpinRes_{min}$	80 kWh
DC-bus capacitance	Cdc	0.01 F
Hybrid grid 1		
Initial DC-bus voltage	$V_{DC_{init}}$	1000 V
DC-bus voltage reference	$V_{DC_{ref}}$	1000 V
Hybrid grid 2		
Initial DC-bus voltage	$V_{DC_{init}}$	594 V
DC-bus voltage reference	$V_{DC_{ref}}$	594 V
AC RMS voltage	$V_{AC_{RMS}}$	440 V
DC voltage no load	$V_{DC_{NL}}$	594 V
Frequency	$freq$	60 Hz
Inductance	L_s	1.0602 H

6.5.3 Simulation results

To validate the two grid options, hybrid grid 1 and 2, the models are tested on actual load profiles: a transit run, a DP run, and a run validating strategic loading. The transit run validates the enhanced dynamic performance and improved working conditions for the generators. During this run, the battery handles sudden changes and gradually returns to zero supply. The DP run demonstrates that when operating under low power demand, charging the battery keeps the generators at a more efficient load while the battery still achieves enhanced dynamic performance. Lastly, a transit run outside of the optimal load range for the generators is simulated, to validate the strategic loading. This is done by manipulating a transit load profile to be outside of the optimal load range.

Transit run

The power demand from the main propulsion (P_{load}), the power from the ESS (P_{ESS}), and the power from the AFEs (P_{AFE}) are illustrated in Figure 6.19 for hybrid grid 1. Figure 6.20 shows the load profile and the power through the AFEs. Based on the results, it is evident that the working conditions for the generators have improved. Note that P_{AFE} is power supplied by the generators, and can therefore be seen as generator power.

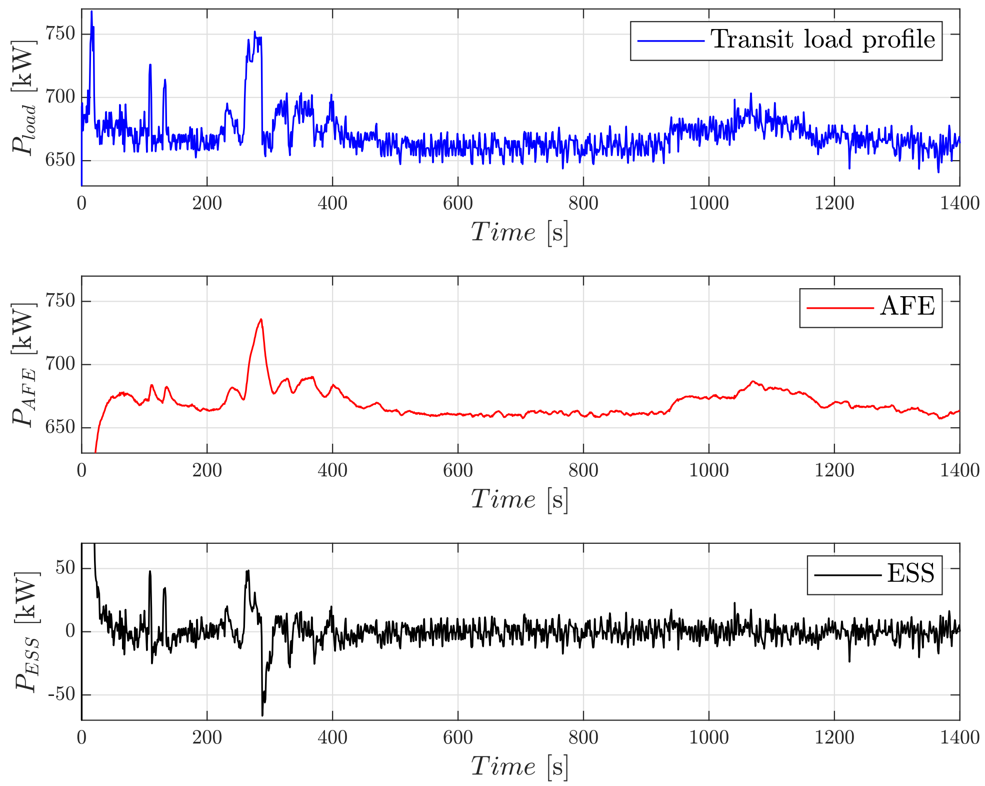


Figure 6.19: Power results during transit for hybrid grid 1.

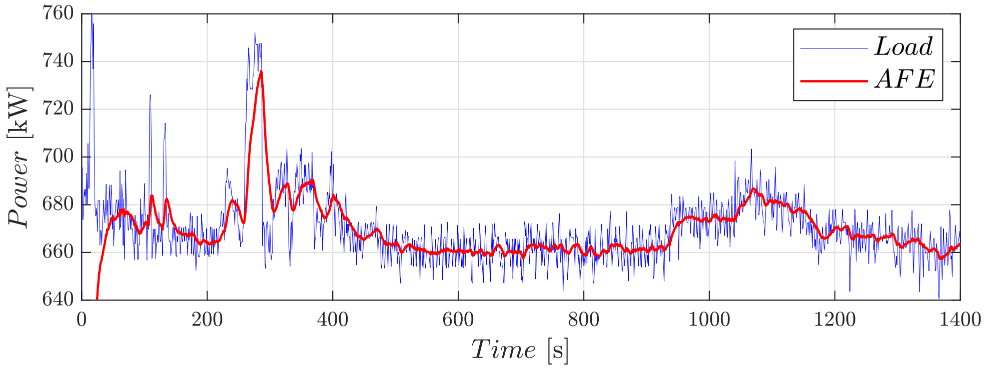


Figure 6.20: Load and generator supply during transit for hybrid grid 1.

The same load profile is simulated for hybrid grid 2, Figure 6.21 illustrates the power supply and load for the main propulsion, the battery, and the diode rectifiers (P_{DR}). Figure 6.22 compares the power supplied by the diode rectifiers (generators) to the load power from the main propulsion. The results are similar to those for hybrid grid 1, with minor differences likely due to the delay factor for each solution. This can be further adjusted if desired.

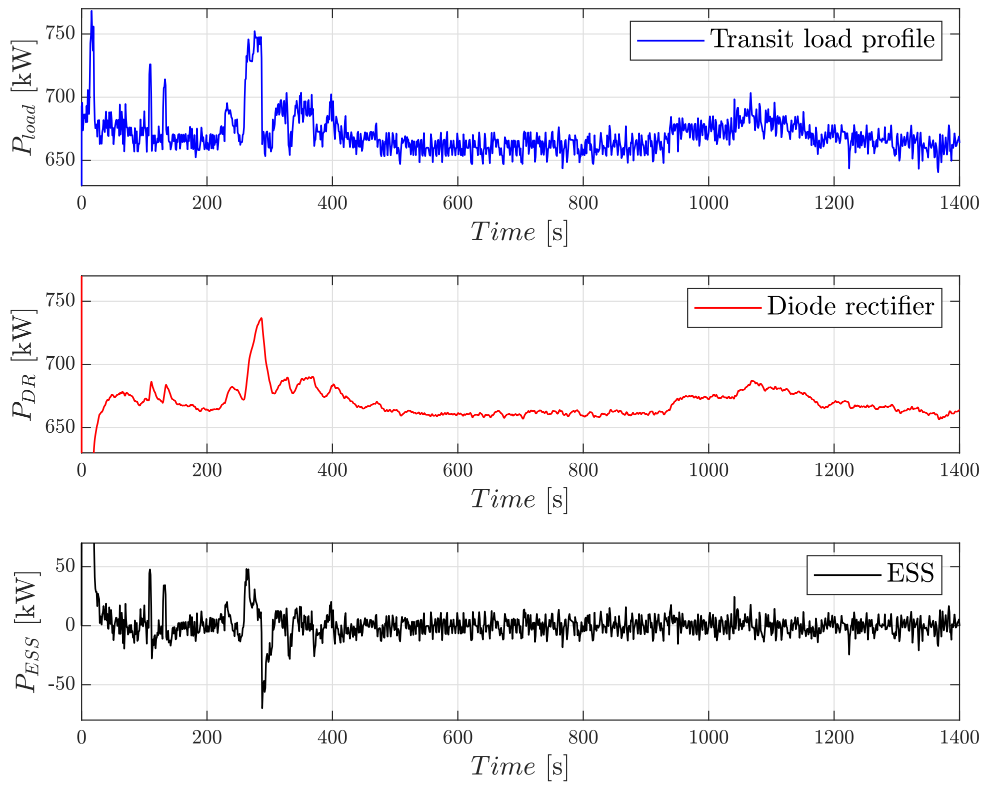


Figure 6.21: Power results during transit for hybrid grid 2.

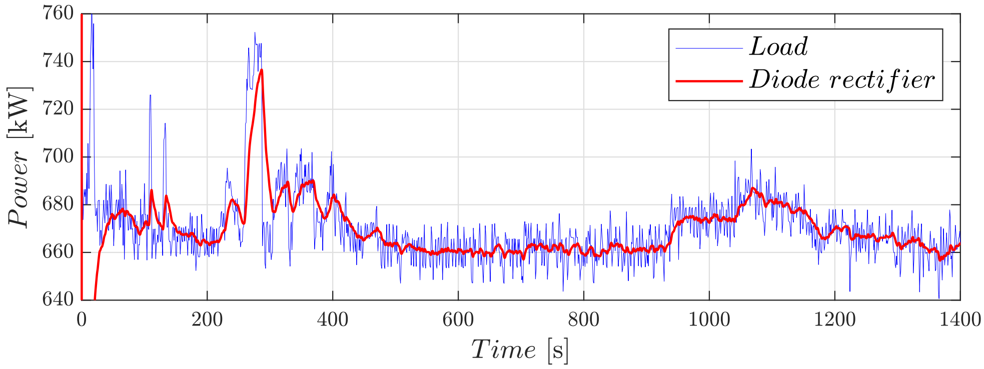


Figure 6.22: Load and generator supply during transit for hybrid grid 2.

DP run

The next run uses actual data from a DP operation. This simulation validates that the generators operate at their best efficiency until the battery reaches its upper limit. Once this limit is reached, the generators supply only the load from the main propulsion.

The initial SOC is set to 75%, with an upper limit of 80%. The results for hybrid grid 1 are presented in Figure 6.23 and Figure 6.24. Note that *AFE power* in Figure 6.23 and *Diode rect power* in Figure 6.25 are supplied by one generator.

The battery continues to achieve enhanced dynamic performance, both during charging and when fully charged. During charging, it ensures a stable load for the generator at efficient power levels. When fully charged, the generator operates less efficiently but more stably than without a battery. The transition occurs after 655 seconds when the battery reaches its upper limit.

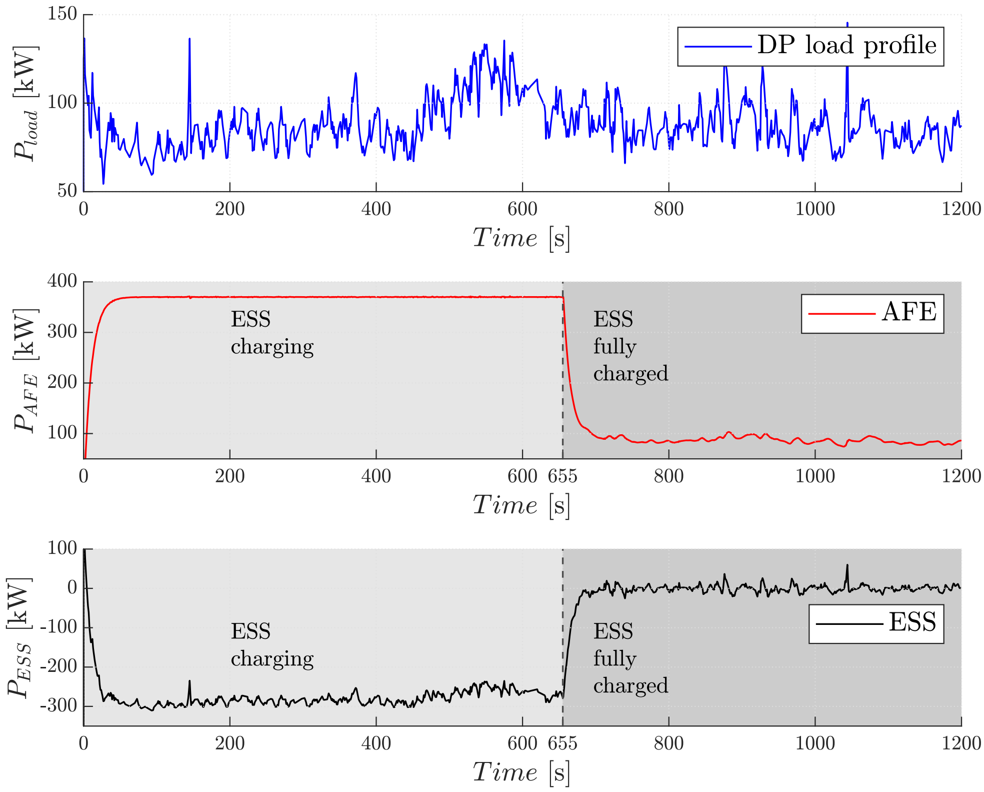


Figure 6.23: Power results during DP for hybrid grid 1.

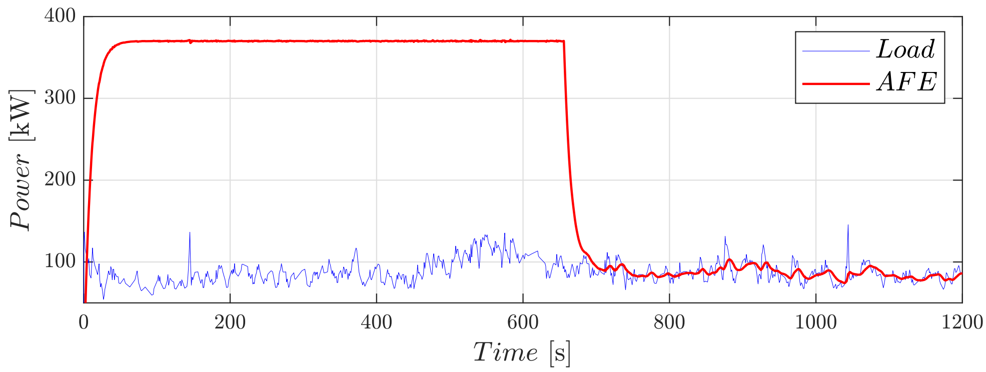


Figure 6.24: Load and generator supply during DP for hybrid grid 1.

The same run has been simulated with hybrid grid 2, and the results are presented in Figure 6.23 and Figure 6.24. The results during DP operations are relatively similar to those of hybrid grid 1, indicating that both solutions are feasible for these operational modes. However, the results alone are insufficient to determine the best option.

Hybrid grid 1 controls both the DC-DC converter from the battery and the AFEs, enabling quick responses to failures in either the battery or the generator. In contrast, hybrid grid 2 needs additional features to ensure a secure power supply if a generator fails. However, hybrid grid 2 has the advantage of easier physical integration since it uses existing diode rectifiers. Additionally, the diode rectifier for the bow thruster can be removed along with its breakers.

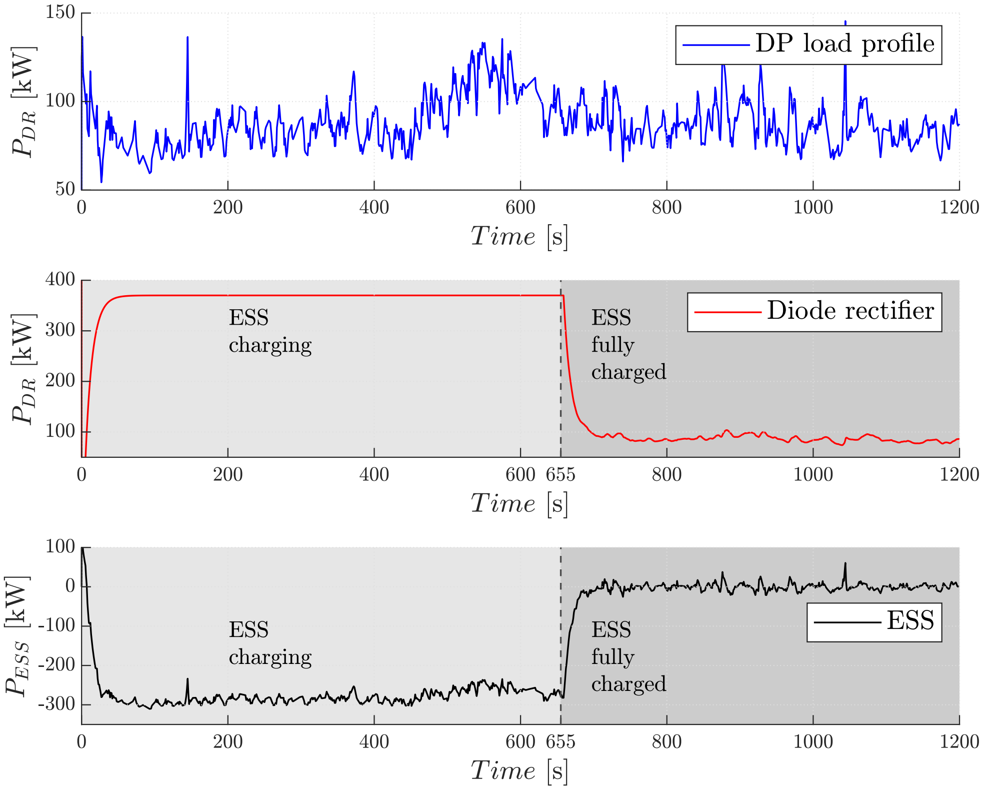


Figure 6.25: Power results during DP for hybrid grid 2.

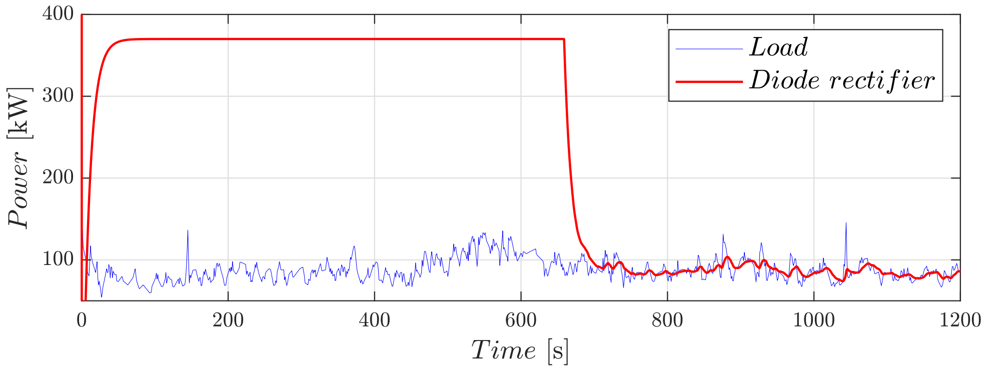


Figure 6.26: Load and generator supply during transit for hybrid grid 2.

Considering that both solutions are feasible regarding the control system and show no significant simulated differences, and based on the discussion in subsection 5.5, hybrid grid 2 is recommended. This solution retains the existing diode rectifiers, which are more cost-effective and require fewer physical changes to the grid. Lastly, hybrid grid 2 is simulated where the load demand is outside of the ideal load range for the generators, to validate strategic loading.

Strategic loading

As the EMS is similar for both grids, the validation of strategic loading is only done for hybrid grid 2. A transit load profile is divided by 1.25 to move it outside of the optimal load range for the generators. The EMS is set to start with the discharging of the battery, and the initial SOC is set to 22%. The simulation illustrates that RV Gunnerus starts with running one generator within its best efficiency, based on Figure 3.7b, and the battery supplies the rest. When the battery reaches its lower limit, 20%, the EMS starts another generator, keeping both generators within efficient load range and charging the battery with the power surplus. Figure 6.27 illustrates that the EMS desires power supply from the diode rectifiers, and the ESS. At time = 500 s, the SOC reaches its lower limit, and another generator is started.

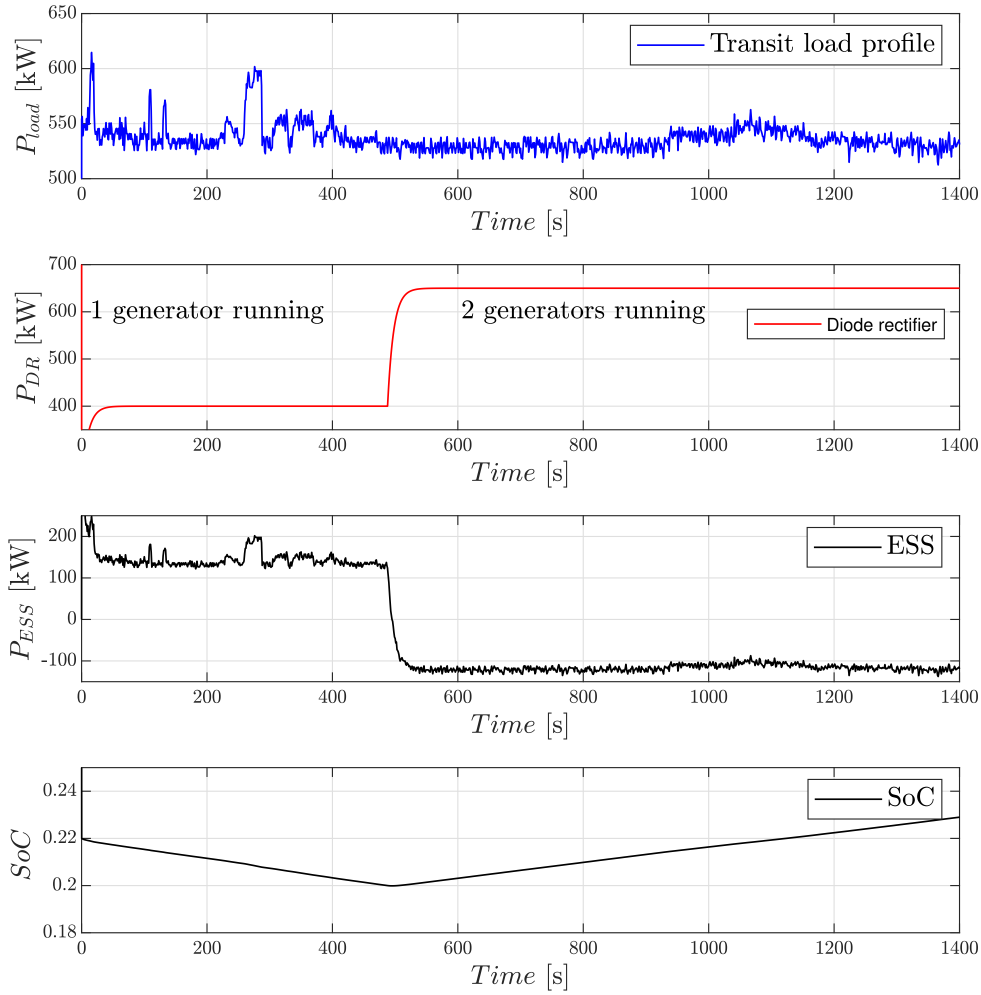


Figure 6.27: Power demand and supply during strategic loading.

7 Use case recommendations

Each chapter focuses on BESS integration in a vessel retrofit from different perspectives. To achieve this, various methods have been used to determine the options and specifications regarding the necessary integration decisions. Each method produced results that were discussed, leading to specific recommendations for the use case of RV Gunnerus. The previous chapters have more details, show different options, and discuss their strengths and weaknesses. This chapter will give an overview of the earlier chapters' recommendations, highlighting the specifications of a possible option in terms of a feasible BESS integration onboard RV Gunnerus. It will also include the main factors that underline each specific recommendation. Recommendations made in a particular chapter that later on get discarded due to factors that become relevant later on in the iterating process will not be mentioned here. Earlier chapters also include more information regarding relevant topics without making a specific recommendation.

7.1 Concept design recommendations

In the subsection 3.2, sizing and selecting, the recommendations made for the use case RV Gunnerus were: *1000 kWh battery capacity, e-rate of 1.1, and SOC window of 20%-80%.*

The main contributions to these recommendations were from the AIS data analysis and evaluation of how RV Gunnerus typically operates. The approach for this calculation looks at what is considered a normal operation for the vessel. The scenario was a relatively short transit from Trondheim harbor with a fully charged battery. The ship uses one diesel generator and the BESS as power supply to achieve transit speed with enhanced dynamic performance. The AIS data analysis showed that a radius of 15 nm from the harbor represents 45% of the vessel's operational area when at sea each year. The desired outcome was for the ship to make the 15 nm transit and then conduct DP operations without starting a second diesel generator. This means the battery must have sufficient power after transit to function as a spinning reserve. The spinning reserve requirement was 75 kWh, and the transit requirement was 508 kWh, with a SOC of 20%-80%, which resulted in a battery capacity of 970 kWh. For a little extra redundancy and a more rounded figure, the suggested recommendation was 1000 kWh.

The recommendation of an e-rate equal to 1.1 was from the transit load profile, with the highest power demand being 1025 kW. In fully electric mode and with a battery of 970 kWh, this results in an e-rate equal to 1.06. Optimally, C-rate would be evaluated, but due to the unknown ampere and voltage of the battery, it is more convenient to use e-rate at this stage.

The recommendation for the SOC window to be between 20%-80% is mainly based on two articles, [37] and [38]. Both studies imply that 20%-80% cycling was a good balance between preserving and utilizing the battery. The type of lithium-ion battery will have an impact, and ultimately, the battery manufacturer knows the batteries the best.

In subsection 3.4, battery type evaluation, the different possible chemistries of a lithium-ion battery were investigated and discussed. The recommended type for RV Gunnerus was the *NMC battery technology.* This recommendation was based on the articles, [41–45]. The NMC batteries are currently the most widely adopted, and they have been demonstrated to be adaptable in terms of power density, energy density, and safety. It is also proven to have the highest energy density, which is essential to achieving the FLEXSHIP goal.

Table 7.1: Recommended parameters.

Parameter	value	unit
Battery size	1000	kWh
e-rate	1.1	-
SoC window	20-80	%
required spinning reserve	125	kWh
grid	hybrid grid 2	-

7.2 Preliminary design recommendations

The following recommendations were made in the physical vessel integration chapter, section 4: *module battery design and the dry provision room as battery space.*

The module battery design offers the highest energy density and flexibility. However, it does not include safety monitoring or cooling, which must be added externally. In comparison, a block battery design system can have these components included but requires more space and is less flexible. There is not a lot of extra space available on RV Gunnerus, and to underscore the FLEXSHIP goal, the module battery design is the best choice.

Despite being the smallest suggested battery space, the dry provision room is strategically located low and in the forward part of the ship. While requiring a small sacrifice in RV Gunnerus's capabilities, this placement is a practical choice that significantly supports the FLEXSHIP goal. It also enhances the ship's stability due to its current aft trim, making it the best option.

In the electrical vessel integration chapter, section 5, it is recommended to use the *hybrid grid 2.*

This option uses a DC-DC converter from the battery to a common DC-bus connected to each of the existing VSDs. To supply the ship's auxiliary mode when running in fully electric mode, it is necessary to have a small AFE connecting the main switchboard to the DC-bus. It also includes removing the AC-DC converter in the VSD for the bow thruster when this is no longer needed. This option is the most flexible solution that is likely to achieve the desired outcomes of the BESS installation and, at the same time, does not require too many new components and changes to the existing electrical grid. This option contributes the most to supporting the FLEXSHIP goal. This option might also be less expensive than some of the alternatives. Even though the retrofit cost is not an essential factor for the FLEXSHIP project, their solutions must be economically viable for the industry to use them in the future.

In the control vessel integration chapter, section 6, there has been suggested how the control architecture can be built. The simulation shows that even with the old VSDs and their passive diode rectifiers, it should be possible to control the battery usage and achieve the desired outcomes of the BESS integration. Briefly explained the simulation shows that it is possible to control battery usage by controlling only the battery's DC-DC converter. The control system also utilizes the existing PMS, and there are no changes to the existing control system. The interface between the new and existing control architecture is handled with a rule-based EMS, that only directly controls the ESS PMS.

7.3 Simulation of the recommended solution for RV Gunnerus

The recommended solution is simulated for a typical voyage for RV Gunnerus, and the parameters are given in Table 7.1. Considering a typical operation pattern for RV Gunnerus, elaborated in section 3.2, a scenario is put together by real load data. RV Gunnerus starts the voyage with 15 minutes of harbor maneuvering, running one diesel generator, and keeping the battery as a spinning reserve. The battery is fully charged from the shore connection. Then, a 1.5 hour transit at 10 knots, running on one generator and the battery. After this, a 2-hour DP operation starts, running one generator and charging the battery. Lastly, returning to berth, transiting for 1.5 hours, and harbor maneuvering for 15 minutes. Note that energy from shore is considered *green* and is therefore seen as *free*. Figure 7.1 illustrates the power demand and the supplied power from the generators and the battery, the SOC is also included. The SOC estimation for the simulations is simplified, but it is included to illustrate the EMS desires depending on the SOC. Based on this SOC calculations, transiting in 10 knots with one generator and the battery costs about 20% battery capacity per hour. While doing DP, the battery is charged with approximately the same capacity per hour.

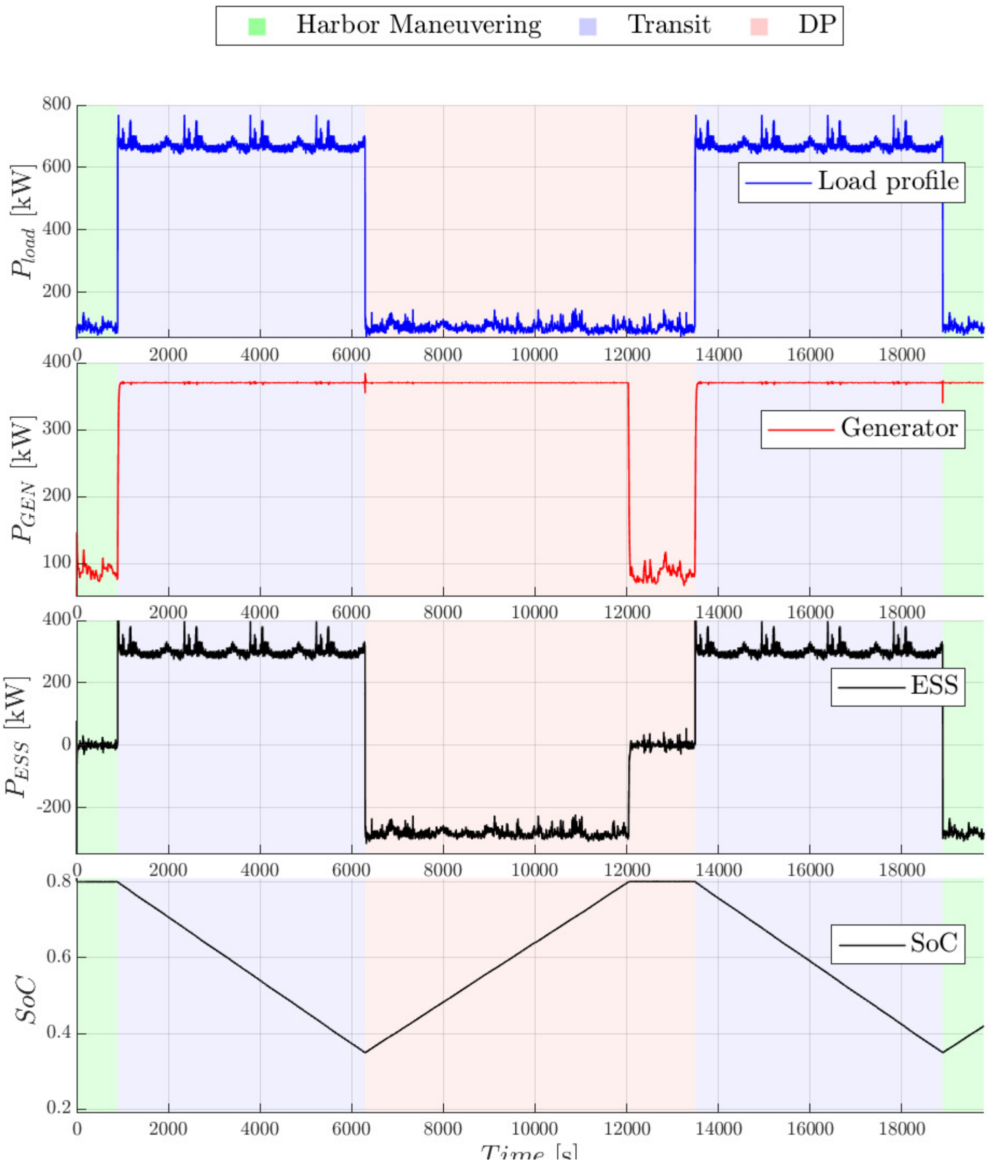


Figure 7.1: Power supply and demand for a typical voyage.

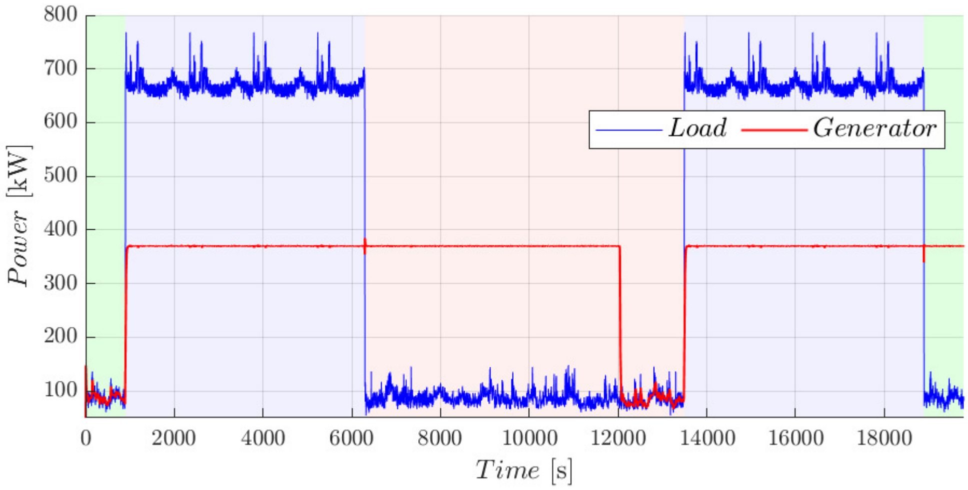


Figure 7.2: Load demand and generator supply for a typical voyage.

To illustrate the difference in working conditions for the generators, the load profile and generator power are plotted together, Figure 7.2. The load profile, blue line, illustrates the main propulsion demand for such a voyage, and if there is no ESS installed, the generators will follow the same power plot. Including running two generators at all times, for spinning reserve during harbor maneuvering and DP, and for sufficient power during transit. With a BESS installed, it is sufficient to run only one generator at all times, at the best efficiency as long as possible.

The fuel consumption for such a run is also calculated based on the SFC curves estimated in Figure 3.6. The fuel consumption is compared to the fuel consumption of a voyage with today's operational pattern. There are several advantages with a BESS. During the harbor maneuvering, there is no need to run two generators, as they do today. Furthermore, with the assumption that the battery is fully charged with green energy from shore, transiting with one generator and the battery, compared to running two generators, is a great advantage regarding fuel consumption. During the DP operation, there is no need to run two generators, as they do today. Additionally, the running generator can operate at an optimal load by charging the battery. On top of this, the battery always works to enhance dynamic performance. The difference in fuel consumption during the voyage and the different operations are presented in Table 7.2. For this voyage, the fuel savings are 110.8 kg, or 21.4%, which is a significant reduction, while keeping the same requirements for spinning reserve and redundancy.

Table 7.2: Fuel savings for a typical voyage.

	Consumption	**Savings [kg]**	**Savings (%)**
Without BESS	544.6 kg	0 kg	0%
With BESS	433.8 kg	110.8 kg	21.4%

7.4 Limitations, uncertainties, and sources of error

There are several uncertainties and sources of error already mentioned in this thesis, and the overarching uncertainties for the use case are discussed in this section. The operational modes, defined in subsection 2.2, are to some extent based on AIS data for 2023, which is considered sufficient. However, the load profiles for the different operational modes are based on two days of data, which may lead to sources of error regarding load demand and fuel consumption. This data is the basis for much of the estimations, simulations, and calculations conducted. Although the data set optimally should consist of a lot more days or even years, it does not impact the methodology. The calculated SFC curve for the generators, Figure 3.5b, is used to define savings and optimal power supply for the generators. This graph was made using a curve fitting method as shown in Figure 3.5a. One can see that some of the data varies a lot from the estimated red line, especially from around 100 kW load and down to 0 kW. However, this does not undermine the method.

Regarding the physical integration and the battery placement, there are some uncertainties. As the physical size in this thesis is based on the SEABAT report [42], and not the actual battery manufacturer for this retrofit, the physical size and required space for auxiliary equipment could differ. Meaning that the dry provision room may not be sufficient. The exact weight of the battery system could affect the stability different from this thesis's calculations.

As this thesis stops at the preliminary design, the electrical grid is considered in a simplified way. The ratings for the power electronics, their interaction with each other, and their contribution to the grid power quality are not quantified. However, a retrofit is an iterative process, necessitating a manageable scope of analysis during each stage.

For the control integration, the simulations only look at the DC-bus and do not include hotel loads and the AC grid. It simulates feasibility and does not include safety measures, and both the PMS and EMS are limited to functionality during normal operation. To be more realistic, the simulation could also have higher fidelity, with more details in each component.

This thesis uses RV Gunnerus as an example of the early stages of a proposed retrofit process. It has several limitations, uncertainties, and sources of error. The recommendations made here need to be re-evaluated in the next steps and are not meant as the final solution.

8 Conclusion

This thesis explored the process of retrofitting a hybrid marine vessel with a BESS. A literature study was conducted on aspects of the integration process, including physical, electrical, and control integration. Scientific articles, industry experience, and class society requirements were studied. This basis sets the boundaries for integration, together with the thesis' use case, RV Gunnerus, and its stakeholders. The stakeholder FLEXSHIP had an overall goal of a complete battery integration solution for the electrification of marine vessels. FLEXSHIP aimed for a safe, flexible, scalable, and reliable solution, which influenced this thesis's recommendations.

The battery electrical size and rating were evaluated based on operational pattern and power demand. The battery placement and its effect on stability were estimated, together with battery chemistry and battery type, e.g., module and rack. Different electrical topologies were discussed, prioritizing flexibility and keeping most of the existing equipment. Lastly, various control systems were analyzed, primarily on the EMS and PMS level.

Studying the vessel and its stakeholders, i.e., operators, class society, and owners, were considered relevant parameters for battery sizing. Regarding the vessel, the power consumption under different operations and at different speeds, together with generator data, was of interest. Both the operators and class society have requirements regarding redundancy and spinning reserve. The owners may have limitations to the cost or desired outcomes for the retrofit.

For placement, it was vital to understand the current status regarding space and stability. Due to stability regulations, some options were not feasible. Furthermore, even if a placement adhered to regulatory guidelines, it might still have been sub-optimal if it negatively impacted the vessel's stability. For most retrofit cases, available space is a limiting factor, and a module-based battery was recommended. Space for auxiliary equipment and safety measures also had to be ensured.

Regarding the grid topology, it was desired to keep most of the existing electrical power electronics. In the case of a retrofit where the vessel has VSDs, keeping the existing AC-DC rectifier was prioritized. Solutions for both passive and active converters were proposed. For both options, a hybrid grid topology with an AC main switchboard and a DC-bus was recommended. A DC-bus might have reduced the required amount of power converters, together with the flexibility of the number of battery packs. In the passive solution, where there was a desired outcome to be able to operate fully electric, a relatively small active converter had to be installed to supply the AC loads from the battery.

A rule-based control system was determined to offer the most reliability and flexibility. A rule-based EMS that consistently targeted optimal generator load based on SFC curves was established. This approach proved relatively simple to set up while demonstrating flexibility and scalability. When the generator operation deviated from the optimal load, the EMS ensured that the battery was either charged or discharged to regulate the generator load accordingly. The EMS directly controlled either the AFE PMS or the ESS PMS, depending on the active or passive solution employed. On the PMS level, enhanced dynamic performance was achieved by ramping up or down the generator load.

For RV Gunnerus, the recommended solution resulted in a fuel reduction of 21.4% for a typical voyage. This is a significant reduction and demonstrates that a battery retrofit is environmentally beneficial for such a vessel. A cost analysis would be needed to determine whether it is economically beneficial.

Retrofitting marine vessels with batteries can have a positive global impact by reducing maritime pollution and supporting the transition toward a more sustainable industry. By adopting battery technology, vessels can operate more quietly and with greater energy efficiency, particularly in hybrid configurations where batteries complement traditional engines. Additionally, battery retrofits can lower fuel consumption and maintenance costs, making them economically attractive for ship operators. International regulations are aimed at reaching net-zero greenhouse gas emissions from shipping by 2050, and to achieve this, innovative solutions such as battery energy storage systems are vital.

8.1 Further work

There are several aspects of the presented material that can be further continued. Suggested points include:

- Continue to the next iterations and delve deeper into physical, electrical, and control integration.
- The ratings of new power electronics are not evaluated, and the integration of new equipment with the existing can be investigated.
- The BMS, with its SOC and SOH calculations, are simplified in this thesis and can be integrated into the simulations, together with battery degradation.
- Safety features, e.g., blackout prevention in the control system, can be added to truly prove feasibility.
- The simulation can be expanded to include the AC side, this would be a more precise picture of the reality.
- The rule-based control system can be optimized with an optimized-based control system on top, with a rule-based as a fall-back system. This can improve fuel consumption and add features such as making the control system understand what operation is ongoing.
- A cost analysis can be conducted to evaluate the economic aspect of such a retrofit.
- The process should be tested on other use cases in order to verify the method.

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APPENDIX

A FLEXSHIP members and roles

Name	Role in Project/Value Chain	Resources
BRUSSELS RESEARCH AND INNOVATION CENTER FOR GREEN TECHNOLOGY	Coordinator, battery design, digital twin energy storage systems.	Access to state-of-the-art testing and production facilities.
FRAUNHOFER GESELLSCHAFT RESEARCH ORGANIZATION	Battery system design & system safety, Energy management.	State-of-the-art BMS facilities/platform.
AVESTA BATTERY & ENERGY ENGINEERING	Battery system provider, safety aspects.	Cutting edge battery tester and a battery pack tester.
DAMEN RESEARCH DEVELOPMENT & INNOVATION BV	Spec. and requirements provider, HiL testing.	Electrical power lab and HiL facilities.
FUNDACION CENTRO TECNOLOGICO SOERMAR	Know-how ship and shipyard requirements and specifications. WP1 leader.	Know-how standards applicable design and construction of vessels and database updated of International Standards, Rules and Regulations.
FAIVELEY TRANSPORT TOURS SAS	Provider of DC Switchboard technology.	Technology provider and cutting edge know-how on charging capabilities.
RINA SERVICES SPA	Know-how standardization and requirements	Know-how on regulatory compliance, classification and technology qualification methodologies.
NORGES TEKNISK-NATURVITENSKAPELIGE UNIVERSITET	Provider DEMO-1 and know-how sustainable maritime power systems	R/V Gunnerus, hybrid power lab for full-scale setup testing marine electric and hybrid propulsion.
SIVAS CUMHURIYET UNIVERSITESI	Experts in power electronics architecture.	Testing laboratories for power electronics, specialized in maritime solutions.
FOUNDATION WEGEMT – A EUROPEAN ASSOCIATION OF UNIVERSITIES IN MARINE TECHNOLOGY AND RELATED SCIENCES	Communication, dissemination, and skills development	WEG network of universities and links to wider international waterborne stakeholder community.
VLAAMSE INSTELLING VOOR TECHNOLOGISCH ONDERZOEK N.V.	Low voltage DC architecture design and protection system.	State-of-the-art Bipolar DC Lab infrastructure.
INSTITUTE FOR SUSTAINABLE SOCIETY AND INNOVATION	Validation and requirements.	Cross-cutting research and innovation laboratories for interdisciplinary research and networking
DNV AS	Simulation Software.	Vessel simulator based on CyberSea simulator platform
KOCAELI BUYUKSEHIR BELEDIYESI	Provider of DEMO-2.	Municipality company providing ship and route requirements and access to demonstration area/route.
ELKON ELEKTRIK SANAYI VE TICARET ANONIM SIRKETI	Ship electrical system integrator	PMS modules use to integrate and validate PMS for ESS. Main Switchboard revision to integrate/test develop E/E architecture
OTASKI ENERGY SOLUTIONS LTD	Provide insight and knowledge market possibilities. Associated partner	Expert business developer for smart infrastructure and energy systems.

Table A.1: FLEXSHIP program partners [9]

B Technical data SCANIA diesel engine

SCANIA
Scania Engines

Marine auxiliary engines
16-series

DHX
Section 6.

Latest modification date: 091123

Technical data

DI16 49M, with (10-62) or without (10-42) heat exchanger

		1500 r/min	1800 r/min
		PRP	PRP
Gross power	kW	450	500
Specific fuel consumption	g/kWh		
full load		200	199
3/4 load		195	198
1/2 load		201	198
Heat rejection	kW		
to cooling water		315	352
to exhaust gas		302	327
to surrounding air		23	24
Heat rejection in water circuit for charge air cooler *	kW	50	69
Max. air inlet temperature	°C	73	77
Recomm. water inlet temperature into charge air cooler	°C	48	49
Air consumption	kg/min	32	41
Exhaust flow	kg/min	34	43
Exhaust temperature	°C	516	452
Test conditions: ISO 3046. Rating code: ISO 8528.			

* This value is included in the value of heat rejection to cooling water

10 Part No. 1 588 877 2012:1

C Relevant pages from hydrostatic report RV Gunnerus

polarkonsult
naval architects & marine engineers

Norges Teknisk Naturvitenskaplige Universitet

NTNU

RV Gunnerus
- LNVZ –

Endelig Stabilitet
Forlengelse 2018-19

C1	Etter krengeprøve 24.02.19	28.03.2019	AM		
C	Revidert iht Kommentar SD	21.12.2018	AM		
A	Utgitt etter intern kontroll	06.12.2018	AM		
U	Basis 12033 Rev A 10.04.2015	30.11.2018	Arne Markussen	ES 05.12.18	
Rev	**Description**	**Date**	**Sign**	**Controlled**	**Approved**

Dok Nr: 18179-RX-03
Printed on: mars 28, 2019
File: N:\M18\18179 Gunnerus - tegninger for ombygging\Dokumenter\Calculations\Stability\18179 Foreløpig stabilitet Gunnerus forlengelse Rev C.docx

3.8 Tabellarisk oversikt over lastekondisjonene

		Vekt (tonn)									DW	d, mld	Trim	GM	KG marg
No.	Tekst	Bro	FV	VB	Div	Utr	Rom	Dekk	RD	Pers	(t)	(m)	(m)	(m)	(m)
1	Lett utrust, 100%	49,5	59,6	0,0	5,5	7,5	0,0	0,0	8,5	0,0	130,6	2,687	-0,402	1,792	1,063
2	Lett utrust, 10%	5,0	5,7	0,0	18,3	7,5	0,0	0,0	8,5	0,0	44,9	2,321	0,439	1,895	0,732
3	Tungt utrust, 100%	49,5	59,6	0,0	5,5	43,8	0,0	0,0	8,5	2,0	168,9	**2,786**	-0,011	1,634	0,622
4	Tungt utrust, 10%	5,0	5,7	0,0	18,3	43,8	0,0	0,0	8,5	2,0	83,3	2,421	0,831	1,684	0,294
5	Max Dekkslast, 100%	49,5	59,6	0,0	5,5	7,5	0,0	38,5	8,5	0,0	169,1	**2,786**	-0,002	1,608	0,593
6	Max Dekkslast, 10%	5,0	5,7	0,0	18,3	7,5	0,0	38,5	8,5	0,0	83,5	2,421	0,841	1,654	0,259
0	Lett skip	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	2,169	0,364	2,262	

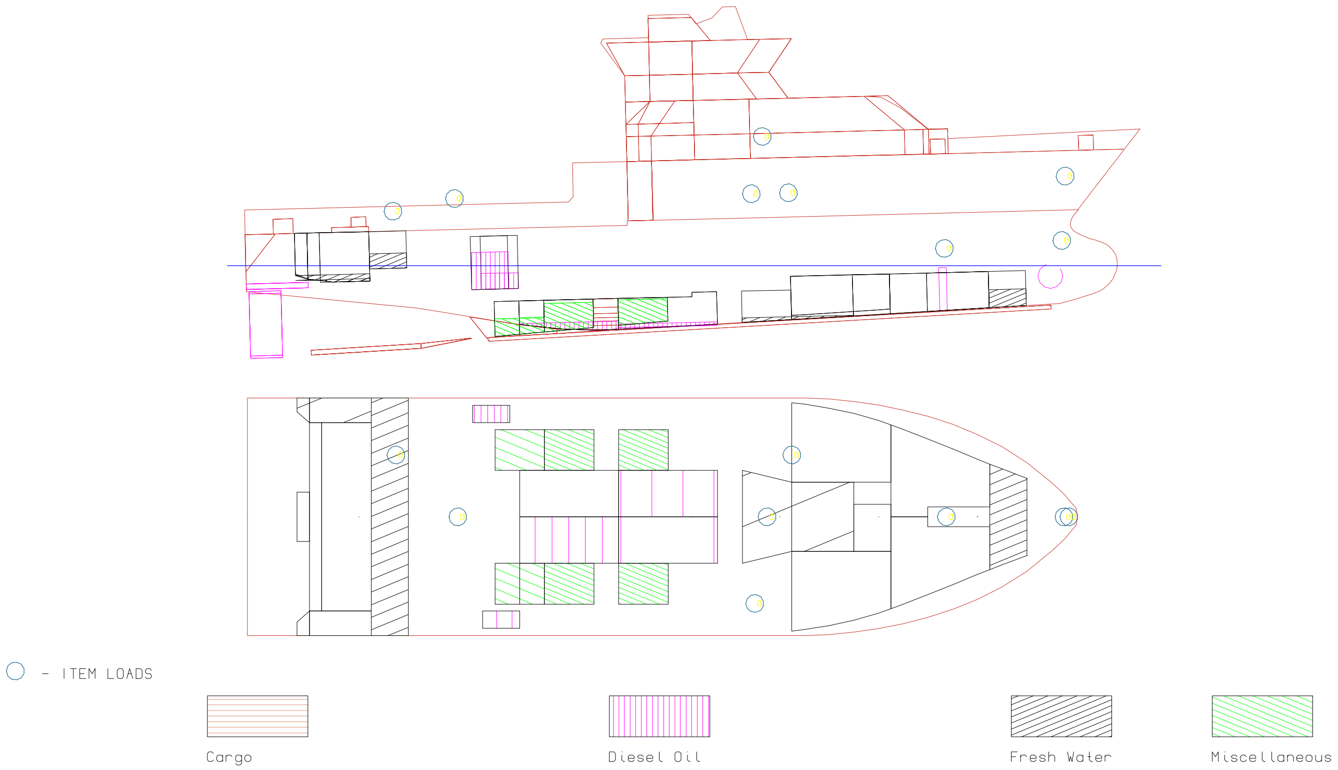
3.9 Kommentarer til intakt stabilitet, Marginer

Alle kondisjoner oppfyller kravene med god margin.

3.10 Utskrift av lastekondisjonene

Etterfølgende sider

Loading Condition code : 6
Condition Id. text : Maks Dekkslast ankomst, 10%



WEIGHT LOADS

Part no.	Id.text	Weight (MT)	Load (%)	Density (MT/m3)	Distribution Aft (m)	Distribution Fore (m)	LCG (m)	TCG (m)	VCG (m)	FSCT Moment (MT*m)
1	Mannskap, stores og proviant									
-	6 mannskap og pers eff	0.600			4.50	5.50	20.000	0.000	7.561	
-	Proviant	1.000			4.50	5.50	32.000	0.000	3.061	
-	Stores forpeak	1.000			4.50	5.50	32.200	0.000	5.661	
-	Stores forut nede	1.000			4.50	5.50	27.250	0.000	2.861	
		3.600					28.736	0.000	4.478	
2	Diverse tanker ankomst									
-	No 7 sb #22-26 Black sew	2.913	90.0	1.0000	11.00	13.00	11.991	2.666	0.605	0.75
-	No 7 p #22-26 Grey sew	2.913	90.0	1.0000	11.00	13.00	11.991	-2.666	0.605	0.75
-	No 8 #20-22 Sludge	0.766	50.0	0.9000	10.00	11.00	10.494	2.661	0.342	0.34
-	No 9 #18-20 Waste	0.803	50.0	0.9000	9.00	10.00	9.493	2.686	0.287	0.32
-	No 10 #18-22 Bilge	1.743	50.0	1.0000	9.00	11.00	9.969	-2.673	0.314	0.73
-	No 14 sb #28-32 Black w	2.787	95.0	1.0000	14.00	16.00	14.987	2.662	0.683	0.75
-	No 14 p #28-32 Grey w	2.787	95.0	1.0000	14.00	16.00	14.987	-2.662	0.683	0.75
		14.713					12.673	-0.032	0.569	4.38
3	Lett vitenskaplig utrustning									
-	Lab og data utrustning	1.500			4.50	5.50	21.000	-2.500	5.261	
-	Utrustning container dekk	5.000					5.000	-2.500	4.913	
-	Prøver o.l. i lager	1.000			4.50	5.50	19.500	3.500	5.261	
		7.500					10.133	-1.700	5.029	

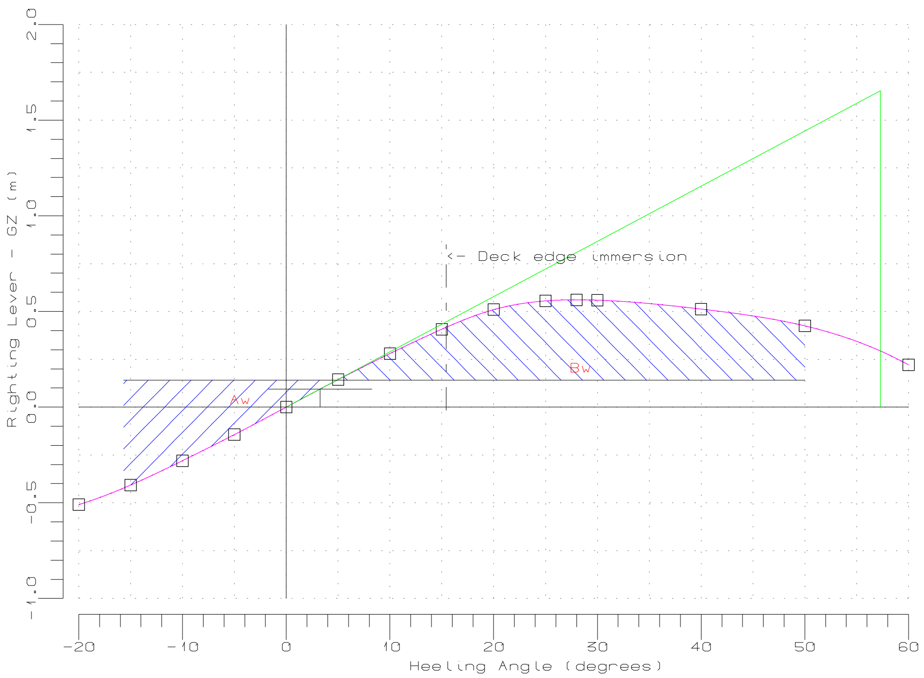
.... to be continued on next page

Part no.	Id.text	Weight (MT)	Load (%)	Density (MT/m3)	Distribution Aft (m)	Distribution Fore (m)	LCG (m)	TCG (m)	VCG (m)	FSCT Moment (MT*m)	
4	Dekkslast										
-	Dekkslast akterdekk	38.500					7.500	0.000	5.363		
5	Brennolje 10%										
-	No 6 sb #20-A FO settl	1.793	27.8	0.8300	10.00	14.00	12.366	0.814	0.231	1.83	*
-	No 6 p #20-A FO	0.000	0.0	0.8300	10.00	14.00	13.178	-0.291	-0.099	1.83	*
-	No 11 sb #17-20 FO serv	0.551	30.0	0.8300	8.50	10.00	9.250	4.150	1.985	0.03	*
-	No 11 p #16-19 FO serv	1.285	70.0	0.8300	8.10	9.60	8.850	-4.150	2.416	0.03	*
-	No 15 sb #A-I FO	0.342	5.0	0.8300	14.00	18.00	15.437	0.481	0.068	1.83	*
-	No 15 p #A-I FO	1.026	15.0	0.8300	14.00	18.00	15.725	-0.726	0.152	1.83	*
		4.998					12.018	-0.434	0.958	7.37	
6	Ferskvann 10%										
-	No 1 #48-51 TW	2.818	50.0	1.0000	29.00	30.50	29.692	0.000	0.982	6.34	*
-	No 3 sb #32-40 TW	0.000	0.0	1.0000	21.00	25.00	21.985	1.699	0.307	8.04	*
-	No 3 p #32-40 TW	0.000	0.0	1.0000	21.00	25.00	21.985	-1.699	0.307	8.04	*
-	No 5 #28-37 FW	1.845	10.0	1.0000	19.00	23.50	20.775	0.000	0.284	10.55	*
-	No 13 sb # 2- 8 Wing TW	0.248	5.0	1.0000	1.00	4.00	3.045	4.068	2.256	0.23	*
-	No 13 p # 2- 8 Wing TW	0.744	15.0	1.0000	1.00	4.00	2.846	-4.149	2.410	0.23	*
		5.654					22.081	-0.368	0.998	33.43	
7	Rulledempingstank										
-	No 12 # 8-11 TW Roll D	8.467	40.0	1.0000	4.00	5.50	4.751	0.000	2.914	110.52	
	DEADWEIGHT	83.432					10.545	-0.209	3.641	155.70	
	LIGHT WEIGHT, Krpr 24.2	411.800					14.893	0.064	3.465		
	TOTAL WEIGHT	495.232					14.161	0.018	3.495	155.70	

*) Moment of inertia for these tanks are set to maximum independent of filling.

Loading Condition code : 6
Condition Id. text : Maks Dekkslast ankomst, 10%

INTACT STABILITY DATA (GZ-curve, Areas, Particulars & Criteria Control)



Angle (degr.)	GZ (m)	Area (m*rad)
-20.000	-0.510	-0.0952
-15.000	-0.407	-0.0549
-10.000	-0.280	-0.0248
-5.000	-0.144	-0.0063
0.000	0.000	0.0000
5.000	0.144	0.0063
10.000	0.280	0.0248
15.000	0.407	0.0549
20.000	0.510	0.0952
25.000	0.555	0.1421
28.000	0.561	0.1714
30.000	0.559	0.1909
40.000	0.512	0.2851
50.000	0.425	0.3678
60.000	0.221	0.4266

Deck immersion : 15.410 °
Maximum GZ at : 28.000 °
Area, 0 - 30 : 0.1909 m*rad
Area, 0 - 40 : 0.2851 m*rad
Area,30 - 40 : 0.0942 m*rad
Area, 0 - maxGZ: 0.1714 m*rad
GM : 1.654 m

Heel to starboard side
Applied VCG : 3.809 m
TCG : 0.000 m

IMO - WIND & ROLLING DATA
Heel from wind : 3.258 °
Heeling lever : 0.094 m
-Proj.lat.Area : 197.747 m
-Wind mom. arm : 4.591 m
-Wind Speed : 26.000 m/s
-Wind Pressure : 504.000 N/m2

Rolling angle : 18.953 °
- X1: 0.800 , X2: 0.954
- r: 1.074 , s: 0.099
- k: 0.700
Area Aw : 0.1047 m*rad
Area Bw : 0.2506 m*rad
Bw/Aw ratio : 2.3934 -

Table of intact stability criteria

TYPE : IMO A.167 incl wind

Code	Id. text		Req.	Actual value	Concl-usion	KGmax (m)
GZMi1	GZ at angle greater or equal to 30.0°		: 0.20 m	0.559	OK	4.527
GZAng	Angle at which max. GZ occur, ð		: 25.00 °	28.000	OK	4.068
GMMin	Minimum GM		: 0.15 m	1.654	OK	5.313
GZAr1	Area, GZ curve (0.0-30.0)°	*)	: 0.055 m·rad	0.191	OK	4.824
GZAr2	Area, GZ curve (0.0-min<40.0,ß>)°	*)	: 0.090 m·rad	0.285	OK	4.644
GZAr2	Area, GZ curve (30.0-min<40.0,ß>)°	*)	: 0.030 m·rad	0.094	OK	4.451
W&R-1	IMO 2008 ISO Code, Severe wind & rolling, Wind press. =		504.0 Pa	----	OK	4.301

ß : flooding angle
ð : angle for maximum GZ
GZarea : area of righting lever
*) : area will also be limited by angles for equilibrium and 2nd intercept

Intact Stability conclusion ...... : OK

Resulting KGmax .... (m): 4.068
KG (incl. correction) .... (m): 3.809
Intact stability margin .... (m): 0.259

Please note !

-GM is calculated based on metacentric height (KMT) for upright vessel (zero heel)
-IMO Wind & Roll: Recommended max angle of heel from wind is 16 degrees or 80% of angle for deck immersion

Flood Opening Results

Loading Condition code : 6 ,Maks Dekkslast ankomst, 10%

No.	Identification text	Type	OvFl Syst	X (m)	Y (m)	Z (m)	Flooding Angle (degr)	Above Sea (m)
1	Maskinromsvent	Downflooding		9.5	2.3	7.51	**	4.881

Above Sea is vertical distance from opening to sea at equilibrium.
**) Flooding angle is outside of specified heel range.

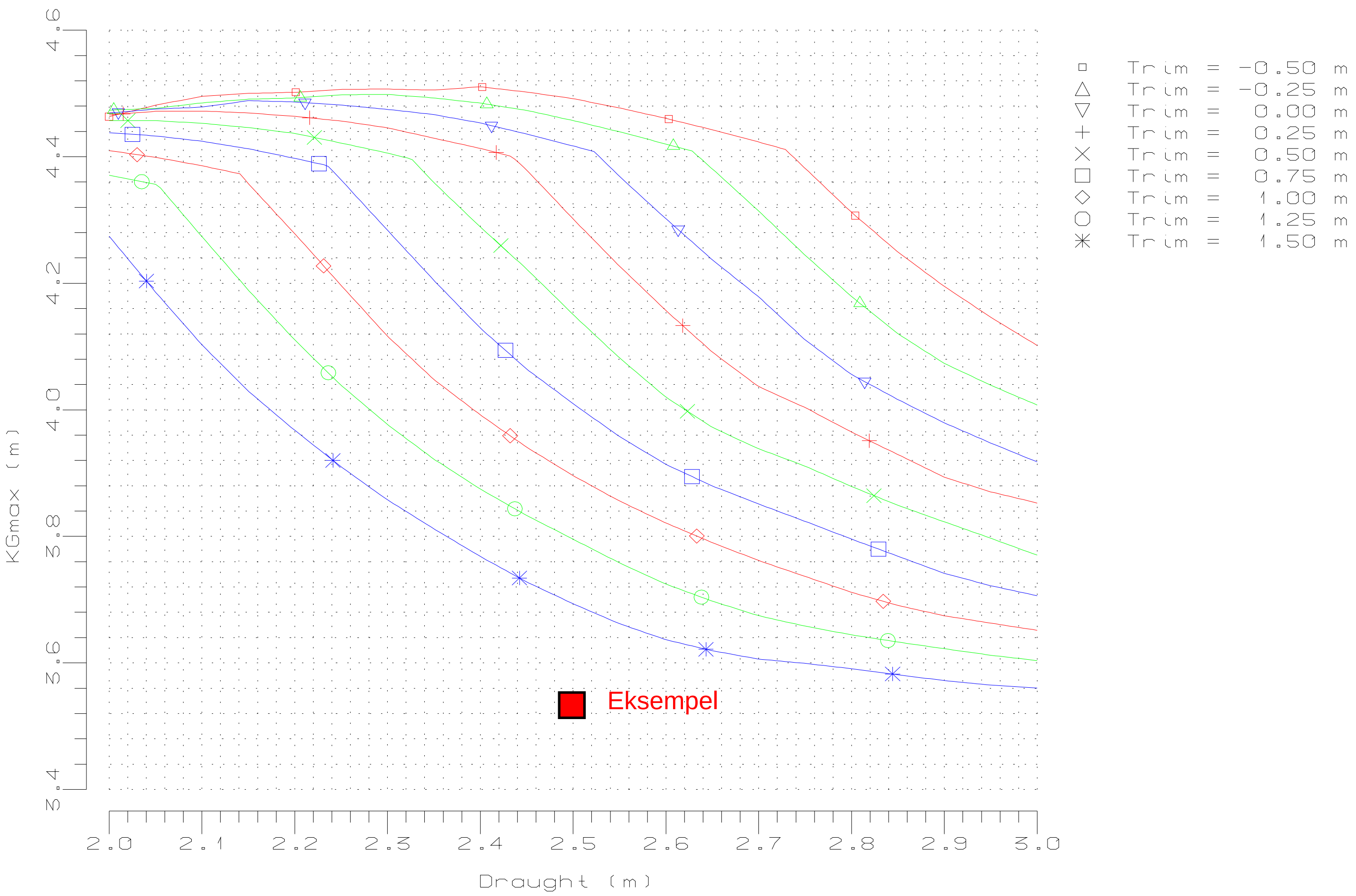
I N T A C T   S T A B I L I T Y   C R I T E R I A

TYPE : IMO A.167 incl wind

No.	Code	Id. text		
1	GZMi1	GZ at angle greater or equal to 30.0°		: 0.20 m
2	GZAng	Angle at which max. GZ occur, ð		: 25.00 °
3	GMMin	Minimum GM		: 0.15 m
4	GZAr1	Area, GZ curve (0.0-30.0)°	*)	: 0.055 m·rad
5	GZAr2	Area, GZ curve (0.0-min<40.0,ß>)°	*)	: 0.090 m·rad
6	GZAr2	Area, GZ curve (30.0-min<40.0,ß>)°	*)	: 0.030 m·rad
7	W&R-1	IMO 2008 ISO Code, Severe wind & rolling,	Wind press.	= 504.0 Pa

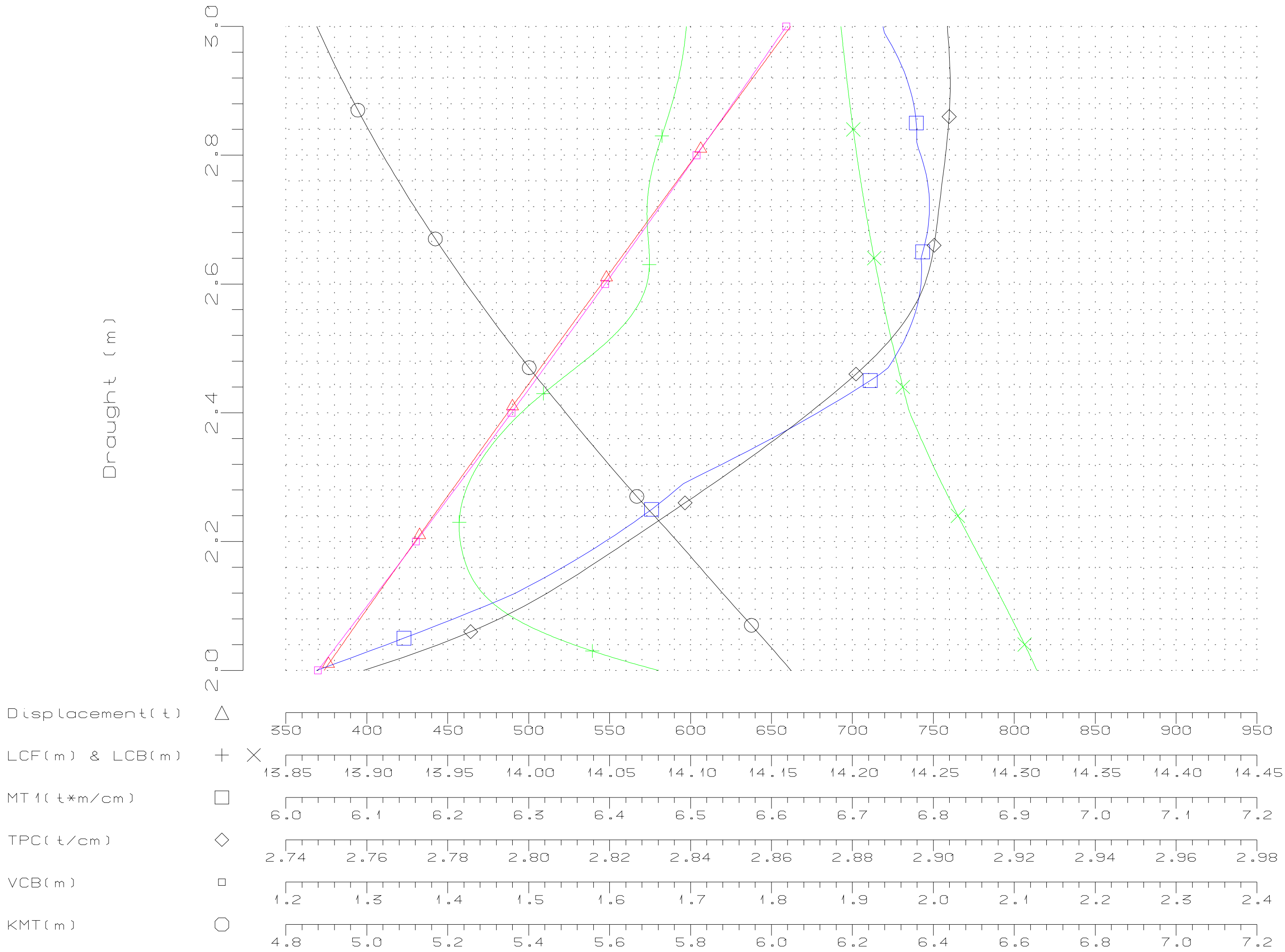
ß : flooding angle
ð : angle for maximum GZ
GZarea : area of righting lever
*) : area will also be limited by angles for equilibrium and 2nd intercept

K G m a x   C U R V E S



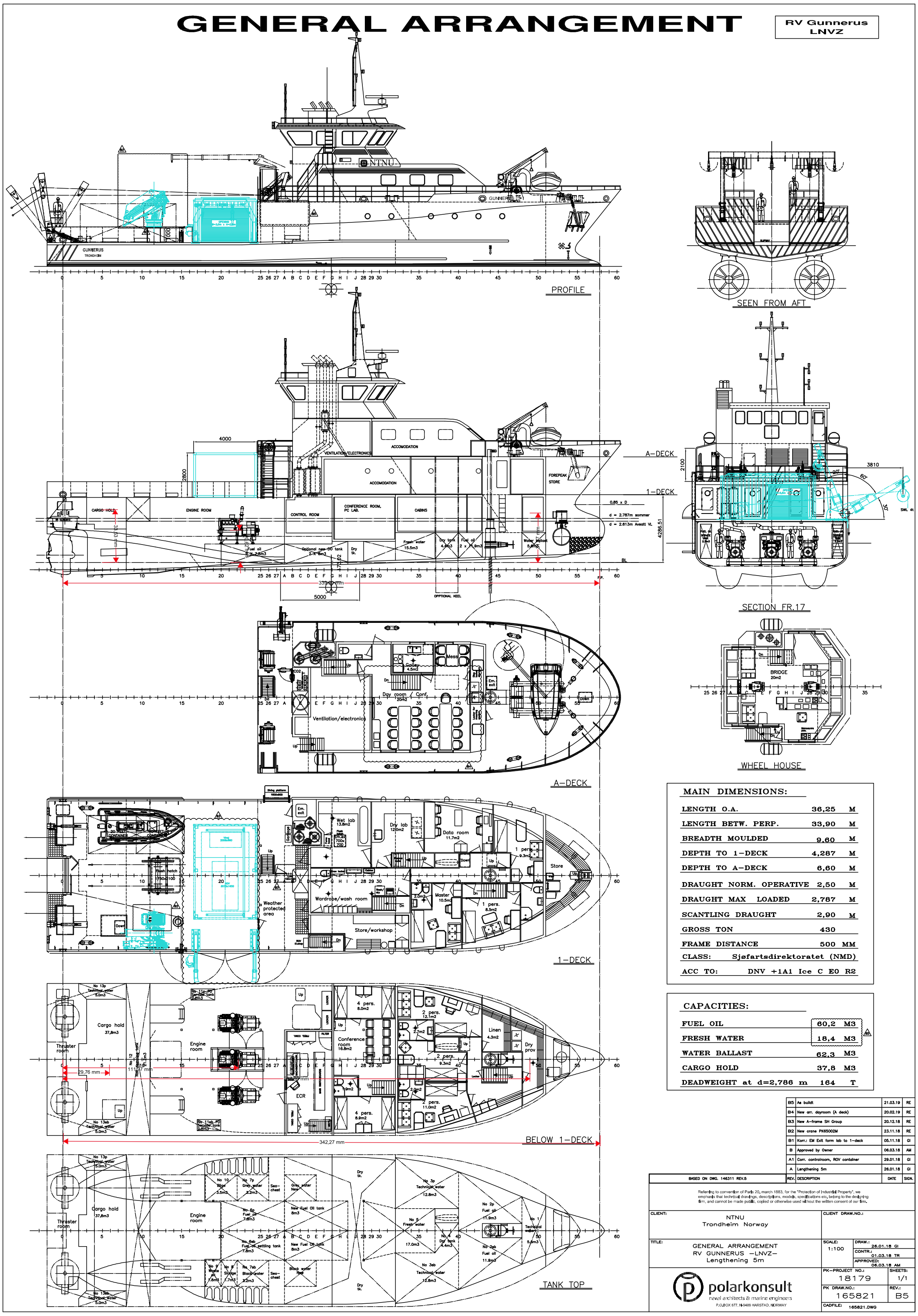
H Y D R O S T A T I C S Sheet 16

TRIM = 0.75 m (+aft)



Draught m	Displ. t	LCB m	VCB m	KMT m	KML m	TPC t/cm	MT1 t*m/cm	LCF m	WSurf m2
2.000	373.58	14.314	1.239	6.048	56.344	2.759	6.04	14.080	366.66
2.010	376.36	14.312	1.246	6.034	56.144	2.764	6.06	14.066	367.72
2.020	379.14	14.310	1.252	6.021	55.943	2.769	6.08	14.052	368.73
2.030	381.93	14.308	1.258	6.007	55.743	2.773	6.10	14.039	369.75
2.040	384.72	14.306	1.264	5.993	55.543	2.778	6.12	14.028	370.67
2.050	387.51	14.304	1.270	5.979	55.342	2.782	6.15	14.017	371.58
2.060	390.31	14.303	1.276	5.965	55.142	2.786	6.17	14.008	372.58
2.070	393.11	14.301	1.282	5.950	54.941	2.789	6.19	13.999	373.54
2.080	395.91	14.298	1.288	5.936	54.741	2.793	6.21	13.992	374.48
2.090	398.72	14.296	1.294	5.922	54.540	2.796	6.23	13.985	375.40
2.100	401.53	14.294	1.300	5.907	54.340	2.799	6.25	13.980	376.31
2.110	404.34	14.292	1.306	5.893	54.139	2.802	6.27	13.975	377.23
2.120	407.16	14.290	1.312	5.879	53.929	2.805	6.28	13.972	378.13
2.130	409.98	14.288	1.319	5.865	53.698	2.807	6.30	13.968	379.07
2.140	412.81	14.286	1.325	5.851	53.467	2.810	6.31	13.966	380.00
2.150	415.63	14.284	1.331	5.837	53.236	2.812	6.33	13.964	380.95
2.160	418.46	14.282	1.337	5.824	53.005	2.815	6.34	13.962	381.92

D General arrangement RV Gunnerus



E Excel calculations for new drought and trim based on inclination test

Data from loading condition 6		
KG	3,81	m
Trim (t), (aft +)	0,84	m
Mean draught (d)	2,42	m
Light ship	411,80	t
DW	83,50	t
LCF (from A.P.)	13,93	m
Trim moment	6,58	MT*m/cm
TPC	2,87	MT/cm
Battery 1 MWh	12,00	t
Battery 2.5 MWh	30,00	t

	LCG [m]	KG_batt [m]	KG_new 1 MWh [m]	KG_new 2.5 MWh [m]
Aft cargo hold	2,950	3,320	3,797	3,781
Engine room	11,090	2,040	3,773	3,713
Dry provision	29,500	3,130	3,793	3,770
Living quarter 1. Deck	29,500	5,580	3,851	3,910

	1 MWh	2.5 MWh
New mean draught [m]	2,462884817	2,525712042
New trim moment [MT*m/cm]	6,73	6,77

Aft cargo hold	1MWh	2.5 MWh
t_added [m]	0,196	0,487
New trim [m] =	1,037	1,328

Subtracted 3.2 tonnes from battery weight due to removal of one diesel generator

Engine room	1MWh	2.5 MWh
t_added [m]	0,037	0,113
New trim [m] =	0,878	0,954

Dry provision	1MWh	2.5 MWh
t_added [m]	-0,278	-0,690
New trim [m] =	0,563	0,151

Living quarter 1. Deck	1MWh	2.5 MWh
t_added [m]	-0,278	-0,690
New trim [m] =	0,563	0,151

1 MWh, d = 2.463 m	Trim [m]	KG [m]	KG_Max [m]	KG_Margin [m]
Aft cargo hold	1,037	3,797	3,911	0,114
Engine room	0,878	3,773	3,988	0,215
Dry provision	0,563	3,793	4,163	0,370
Living quarter 1. Deck	0,563	3,851	4,163	0,312

2.5 MWh, d = 2.526 m	Trim [m]	KG [m]	KG_Max [m]	KG_Margin [m]
Aft cargo hold	1,328	3,781	3,744	-0,037
Engine room	0,954	3,713	3,900	0,187
Dry provision	0,151	3,770	4,318	0,548
Living quarter 1. Deck	0,151	3,910	4,318	0,408

F Generator datasheet

HCM534D

STAMFORD

WINDING 311

CONTROL SYSTEM	SEPARATELY EXCITED BY P.M.G.							
A.V.R.	MX321	MX341						
VOLTAGE REGULATION	± 0.5 %	± 1.0 %	With 4% ENGINE GOVERNING					
SUSTAINED SHORT CIRCUIT	REFER TO SHORT CIRCUIT DECREMENT CURVES (page 7)							
INSULATION SYSTEM	CLASS H							
PROTECTION	IP23							
RATED POWER FACTOR	0.8							
STATOR WINDING	DOUBLE LAYER LAP							
WINDING PITCH	TWO THIRDS							
WINDING LEADS	12							
STATOR WDG. RESISTANCE	0.0049 Ohms PER PHASE AT 22°C SERIES STAR CONNECTED							
ROTOR WDG. RESISTANCE	1.77 Ohms at 22°C							
EXCITER STATOR RESISTANCE	17 Ohms at 22°C							
EXCITER ROTOR RESISTANCE	0.092 Ohms PER PHASE AT 22°C							
R.F.I. SUPPRESSION	BS EN 61000-6-2 & BS EN 61000-6-4,VDE 0875G, VDE 0875N. refer to factory for others							
WAVEFORM DISTORTION	NO LOAD < 1.5% NON-DISTORTING BALANCED LINEAR LOAD < 5.0%							
MAXIMUM OVERSPEED	2250 Rev/Min							
BEARING DRIVE END	BALL. 6220 (ISO)							
BEARING NON-DRIVE END	BALL. 6314 (ISO)							
	1 BEARING				2 BEARING			
WEIGHT COMP. GENERATOR	1393 kg				1395 kg			
WEIGHT WOUND STATOR	657 kg				657 kg			
WEIGHT WOUND ROTOR	563 kg				535 kg			
WR^2 INERTIA	8.0068 kgm^2				7.7289 kgm^2			
SHIPPING WEIGHTS in a crate	1355kg				1395kg			
PACKING CRATE SIZE	166 x 87 x 124(cm)				166 x 87 x 124(cm)			
	50 Hz				60 Hz			
TELEPHONE INTERFERENCE	THF<2%				TIF<50			
COOLING AIR	1.035 m^3/sec 2202 cfm				1.312 m^3/sec 2780 cfm			
VOLTAGE SERIES STAR	380/220	400/231	415/240	440/254	416/240	440/254	460/266	480/277
VOLTAGE PARALLEL STAR	190/110	200/115	208/120	220/127	208/120	220/127	230/133	240/138
VOLTAGE SERIES DELTA	220/110	230/115	240/120	254/127	240/120	254/127	266/133	277/138
kVA BASE RATING FOR REACTANCE VALUES	435	435	435	435	500	520	545	570
Xd DIR. AXIS SYNCHRONOUS	2.63	2.37	2.20	1.96	3.06	2.85	2.73	2.62
X'd DIR. AXIS TRANSIENT	0.14	0.12	0.11	0.10	0.15	0.14	0.13	0.12
X"d DIR. AXIS SUBTRANSIENT	0.10	0.09	0.08	0.07	0.10	0.10	0.10	0.09
Xq QUAD. AXIS REACTANCE	2.16	1.95	1.81	1.61	2.50	2.32	2.22	2.13
X"q QUAD. AXIS SUBTRANSIENT	0.23	0.22	0.20	0.17	0.27	0.25	0.24	0.23
X_L LEAKAGE REACTANCE	0.04	0.03	0.03	0.03	0.05	0.05	0.04	0.04
X_2 NEGATIVE SEQUENCE	0.17	0.15	0.14	0.12	0.19	0.18	0.17	0.17
X_0 ZERO SEQUENCE	0.09	0.08	0.07	0.06	0.09	0.08	0.08	0.07
REACTANCES ARE SATURATED	VALUES ARE PER UNIT AT RATING AND VOLTAGE INDICATED							
T'd TRANSIENT TIME CONST.	0.08s							
T"d SUB-TRANSTIME CONST.	0.012s							
T'do O.C. FIELD TIME CONST.	2.2s							
Ta ARMATURE TIME CONST.	0.018s							
SHORT CIRCUIT RATIO	1/Xd							

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