DC vs. Variable Frequency AC

A grid comparison for a marine modular energy system

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Master's thesis

Master of Engineering, Autonomous Maritime Operations

Turku 3.12.2021

EXAMENSARBETE

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Inriktningsalternativ/Fördjupning: Autonomous Maritime Operations

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Titel: DC vs. Variable Frequency AC – a Grid Comparison for a Marine Modular Energy System

3.12.2021 Sidantal 65 Bilagor 16

Abstrakt

Denna studie har gjorts som slutavhandling vid Yrkeshögskolan Novia, utbildningsprogrammet *Master in Autonomous Maritime Operations*. Studiens beställare är Wärtsilä Oyj Abp.

Målet med slutarbetet är att föreslå en lämplig elnätslösning för ett koncept med marina modulära kraftkällor. I avhandlingen jämförs likströms nät (DC) och växelströms nät (AC) med variabel frekvens. Elnäten har jämförts utgående från ett exempel fartyget, en 150 m långt RoLo fraktfartyg med elektrisk framdrift.

Energimodulerna i denna studie har är monterade i standard 40 fots *High Cube* fartygscontainrar, eftersom fartygscontainern har en befintlig världsomfattande logistik-kedja. För att jämföra elnätstypernas egenskaper med betoning på modularitet, har dieselgenerator-, bränslecell- och batteri-moduler undersökts. Det modulära konceptet kan dock anpassas till alla energikällor som kan konverteras till elektricitet.

Utgångspunkter för designen har varit energieffektivitet, redundans, utbytbarhet och möjligheten att ansluta olika energikällor. Dessa kriterier har valts med tanke på fördelarna både för nutida nybyggen som för framtida obemannade och begränsat bemannade fartyg. Elnätsdesignen har byggts upp kring befintliga komponenter och befintliga energikällor. Verkningsgraderna som använts i denna studie är baserade på förlust-data uppgivna av komponenttillverkarna vid olika driftlägen.

Resultatet av studien är att likströmsnätet är det föreslagna alternativet för ett koncept med modulära energikällor. Likströmsnätet visar fördelar inom energi effektivitet, redundans och anpassning till olika energikällor.

AC nätet med variabel frekvens visar sig dock vara ett konkurrenskraftigt alternativ för ett dieselgenerator upplägg. Eftersom känslig utrustning matas via stabiliserande omvandlare kan huvudnätets frekvens och spänning tillåtas variera, varvid även AC nätet kan dra nytta av dieselgeneratorer med variabelt varvtal och därmed reducerad bränsleförbrukning.

Språk: Engelska Nyckelord: modulär, marin, energi, variabel frekvens AC nät, DC nät

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Nimike: DC vs. Variable Frequency AC – a Grid Comparison for a Marine Modular Energy System

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3.12.2021 Sivumäärä 65 Liitteet 16

Tiivistelmä

Tämä opinnäytetyö on tehty osana ylempää ammattikorkeakoulututkintoa Novia UAS koulutusohjelmassa *Master in Autonomous Maritime Operations*. Tutkielman toimeksiantaja on Wärtsilä Oyj Abp.

Lopputyön tavoite on ehdottaa soveltuvaa verkkoratkaisua alusten modulaariselle energialähderatkaisulle. Tutkielmassa verrataan tasajänniteverkkoa (DC) ja taajuudeltaan vaihtelevaa vaihtosähköverkkoa (AC). Vertailu on tehty sähköisen propulsion omaavan 150 m pitkän RoLo aluksen pohjalta.

Energiamoduulien kehikkona on käytetty 40 jalan *High Cube* standardi merikonttia, jonka etuna on maailmankattava logistiikkaketju. Sähköverkon soveltuvuutta modulaarisuuteen on tutkittu dieselgeneraattori-, polttokenno- ja akustomoduulien kautta, joskin modulaariseen energiaratkaisuun soveltuu kaikki sähköiseen muotoon muutettavat energianlähteet.

Tutkittujen sähköverkkoratkaisujen päävertailukohtina on käytetty energiatehokkuutta, redundanssia, vaihdettavuutta sekä eri energialähteiden kytkettävyyttä. Valittujen vertailukohtien perusteena on soveltuvuus sekä nykypäivän uudisrakennuksille, että tulevaisuuden rajoitetusti miehitetyille sekä miehittämättömille aluksille. Sähköverkkorakenteet pohjautuvat todellisiin laitteisiin ja energialähteisiin. Tehokkuusvertailussa rakenneosien hyötysuhteet perustuvat toimittajilta saatuihin häviötietoihin eri kuormitustilanteissa.

Tutkielman lopputuloksena soveltuvana verkkoratkaisuna modulaariselle energiaratkaisulle ehdotetaan DC verkkoa joka jättää taakseen muuttuvan taajuuden AC verkon energiatehokkuudessa, redundanssissa sekä useimpien energialähteiden liitettävyydessä.

Muuttuvan taajuuden AC verkko osoittautuu kuitenkin varteenotettavaksi vaihtoehdoksi dieselgeneraattori käytöllä. Pääverkon taajuuden sallitaan muuttuvan, sillä herkät laitteet syötetään stabilisoitujen muuttajien kautta. Tämä mahdollistaa vaihtokierrosluvullisten dieselgeneraattoreiden käyttöä joka puolestaan tuo huomattavia polttoainesäästöjä.

Kieli: Englanti Avainsanat: alus, energia, moduuli, AC, DC

MASTER'S THESIS

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Degree Programme: Master of Engineering, Turku

Specialization: Autonomous Maritime Operations

Supervisor(s): Thomas Finne

Title: DC vs. Variable Frequency AC – a Grid Comparison for a Marine Modular Energy System

December 3rd, 2021 Number of pages 65 Appendices 16

Abstract

This study has been made as a part of the master's studies in Autonomous Maritime Operations at Novia University of Applied Sciences. The client of the study is Wärtsilä Oyj Abp.

The aim of this thesis is to propose a suitable electrical grid for a marine modular energy source concept. The studied grid types are Direct Current (DC) and variable frequency Alternating Current (AC). The example vessel in this study is a 150 m combined Roll-on/roll-off and Lift-on/lift-off cargo vessel (RoLo) with electric propulsion.

The energy module size investigated is a standard 40 ft high cube shipping container due to the existing worldwide logistic chain. To evaluate the electrical grid, Genset, fuel cell and battery modules have been investigated as energy sources. Though, the modular energy concept adopts all energy sources that can be converted to electricity.

The key point of comparison for the grid types are energy efficiency, redundancy, replaceability and adoption of various energy sources. These criteria have been chosen due to their value for both today's vessels as well as future unmanned and reduced manned vessels.

The grid designs are based on existing components and existing energy sources. The efficiency numbers at different load conditions are based on data received from component manufacturers.

The thesis shows that the DC grid is the preferred alternative for a modular energy source concept. The DC grid benefits from higher efficiency, redundancy and adoption of most energy sources.

However, the investigated variable frequency AC grid is a worthy competitor for a Genset solution. As the frequency for sensitive consumers is stabilized, it is allowed to vary for the main grid. This enables the use of variable speed Gensets with reduced Specific Fuel Oil Consumption (SFOC) also for the AC grid.

Language: English Key words: modular, marine, energy, variable frequency AC grid, DC grid

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Definition of terms

ABB	ABB Ltd
ABS	American Bureau of Shipping
AC	Alternating current
AES	All Electric Ship
AFE	Active Front End
BMS	Battery Management System
CAPEX	Capital Expenses
CBM	Condition Based Maintenance
DC	Direct current
EMI	Electro Magnetic Interference
EMS	Energy management system
ESS	Energy Storage System
Genset	Generator with ICE prime mover
GHG	Green House Gases
ICE	Internal Combustion Engine
IMO	International Maritime Organization
LOA	Length Overall
MCCB	Molded Case Circuit Breaker
NMC	Lithium Nickel Manganese Cobalt Oxide – Battery Chemistry
OEM	Original Equipment Manufacturer
OPEX	Operational Expenses
PEMFC	Proton-Exchange Membrane Fuel Cell
PMS	Power Management System
PWM	Pulse Width Modulation
RoLo	Roll on Lift off
rpm	revolutions per minute
SFOC	Specific Fuel Oil Consumption

Definition of terms

SOC	State Of Charge
SOLAS	Safety Of Life At Sea – An central IMO rule book
THD	Total Harmonic Distortion
VFD	Variable Frequency Drive

1 Introduction

The ongoing climate change pushes shipping, amongst other industries, to reduce their emissions to minimize global warming. The latest report from the Intergovernmental Panel on Climate Change (IPCC) report published 9.9.2021 is a good reminder that the issue is very much present. Within the shipping industry, one of the most central targets is the IMO 2050 goal, which is to reduce the annual Green House Gas (GHG) emissions from shipping by at least 50% by 2050 compared to the emission level of 2008.

According to (IMO, 2021, p. 2), the GHG emissions from shipping covered 2,89% of the world's anthropogenic emissions in 2018. The GHG emissions from shipping include carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), all expressed in CO_2-eqvivalent (IMO, 2021, p. 1). In shipping, the GHG's are results of the chemical energy of the fuel being converted to heat, electricity and propulsion energy. Reaching the IMO 2050 goal requires a combination of technological development, utilizing of new, low GHG fuels and energy optimization of the vessels.

The shipping industry is in a phase of implementing several new energy sources. For example, ammonia for deep sea shipping, whilst hydrogen and battery solutions for short sea shipping are developed by several actors. In the process of choosing the fuels of tomorrow many factors are weighing in. From the point of nature, the chosen fuels Well to Wake GHG emissions [g/MJ], or life cycle emissions play the most central role. The Well to Wake GHG emissions will vary as technological obstacles are overcome. Estimating the future dominant marine fuels is hard, a fact that need to be considered in the vessel's design phase. Designing vessels with a flexible propulsion energy solution could be a way of future proofing the fleet.

1.1 Purpose

The shipping industry has a long tradition of building one of a kind vessels and small number vessel series, where the sister vessels are seldom fully identical. In the aviation and car industries, the manufacturers produce a large number of identical crafts to cut the design and development costs. The future of shipping, with reduced crew in combination with a higher level of autonomy and complexity requires a similar approach with standardized parts and modules. Especially if the step of fully autonomous vessels is to be reached.

A high level of standardization with common spare modules benefits several parties in the shipping industry. The shipbuilders and ship equipment manufacturers are able to cut production costs and the shipowners will benefit of lower ship investments and common spare parts for the fleet. This results in lower transportation costs and most important, a lower impact on the nature as resources in form of raw material and energy are saved.

The same approach with standardized energy modules can be used for ships. Modules which can be easily swapped in case of a failure or for preventive maintenance by the Original Equipment Manufacturer (OEM) as a service for the customer. By converting the energy source to electricity, virtually any energy source or combination of energy sources can be used to power these ships. The standardized module approach enables the shipowner even to change the energy source of the vessel during its lifetime, for example in case of a route change into restricted areas or a vessel midlife upgrade. Providing pre-maintained or pre-charged energy modules to shipping companies are other possible business areas. This flexibility of utilized energy sources extends the lifetime of the vessel beyond the future emission restrictions.

The aim of this thesis is to propose a suitable electrical grid solution for a vessel utilizing standardized modular energy sources with various fuels.

1.2 Research Question

As mentioned in the previous chapter, the adoption of various energy sources and a modular design can be achieved by converting the energy sources to electricity. The main focus of this thesis is to compare a DC grid and a variable frequency AC grid and to evaluate their suitability for a modular energy source concept. The variable frequency AC grid was chosen as previous research has shown substantial benefits of the DC grid compared to the traditional fixed frequency AC grid. To deepen the knowledge, it is interesting to examine which benefits the AC grid can achieve if the frequency is allowed to vary. The grids are evaluated in essential factors such as energy efficiency, power transmission losses, connection of energy sources, reliability, plant footprint, synchronization, reactive power and harmonics.

The required control system principles to enable a modular energy source concept is also investigated. Both control system layout and necessary software layers are described. The control system functionality is presented with load sharing and fault behavior examples.

1.3 Limitations

The number of changing factors in designing a modular multifuel energy concept is numerous, therefore the focus of this thesis is on the electrical grid design, and in principal extent, the automation design. Other essential fields, such as vessel design, hull shape, displacement, cargo space optimization, energy module mechanical design etc. are excluded from the thesis as each of these fields would require a thesis of their own.

1.4 Methodology

The writer's experience in marine electrical engineering, together with the interest in ship propulsion solutions for future vessels has been the foundation for this thesis. This foundation has been strengthened by the Novia-Turku-Finland held education *Master in Autonomous Maritime Operations*, which this thesis is the final part of.

The thesis process started with the idea to investigate the electrical grid for a modular energy solution. The power range for the example vessel was chosen to 5+5 MW propulsion power. This power range can for example be used for a costal cargo vessel with a length of 150-170 m and a cruising speed of 15-17 knots. The basic grid types, DC and variable frequency AC, were chosen as the main focus of the thesis.

After the basic design was approved by Wärtsilä (personal communication with Technical Director 9.4.2021), the work continued with research in the field. The benefits of the DC grid compared to a fixed frequency AC grid has been studied in several research papers within the marine sector. For example, (Kim, Park, Roh, & Chun, 2018) has written about different DC grid designs and generally about the benefits, while (Eikeland Holmefjord;Husdal;de Jongh;& Torben, 2020) have evaluated the benefits of the DC grid based on actual measurements from a wind farm supply vessel over a period of three months. The availability of earlier research regarding a marine variable frequency AC grid is however very limited.

The work continued with choosing of suitable components such as generators, power converters and transformers. The component properties were discussed with the equipment manufacturers to ensure that the most suitable and efficient products were chosen for further analysis. Regular online meetings have been held during the thesis writing process with Wärtsilä experts (Technical Director & General Manager). Online meetings have also been held with equipment manufacturers such as ABB Oy (Global Product Manager, Generators) and Danfoss Oy (Product Manager, Premium Drives). Isotech Srl has also been consulted regarding transformer design. The equipment manufacturers have provided efficiency values at different load points. These values have been the foundation for the system efficiency comparisons.

The grid design details were further developed from the component data sheets and efficiency numbers together with information from literature, industrial dimensioning tables, national electrical installation guidelines, classification society rules and guidelines as well as research reports in the fields of grid design, power converters and control system designs. The information about the properties of the investigated energy sources are gathered from research reports, with guidance from technical experts in the field.

2 Theory

The theory part of this thesis starts with a presentation of the example vessel in section 2.1. The example vessel has been used as the foundation for comparing the DC and variable frequency AC grid designs. Further, the basic principles of the investigated energy sources are presented in section 2.2. The comparison of the grids, property by property, is presented in section 3.

2.1 Example vessel

To compare the benefits of DC and variable frequency AC grids, an example vessel, m/s Module has been used as a platform. For grid comparison purposes, a number of different energy sources have been studied. The example vessel is powered by Diesel Generators (Genset) and Proton Exchange Membrane Fuel Cells (PEMFC), as main sources of power, combined with batteries for peak-shaving and spinning reserve. Peak shaving improves the vessel's SFOC as the primary energy source can be kept at a steady load whilst consumption peaks are fed from the battery. Spinning reserve improves the SFOC and OPEX costs by allowing the vessel to shut down a number of main energy sources, thus loading the remaining ones with optimal load, whilst the power reserve is covered by the battery. Fewer running main energy sources means fewer running hours and thereby lower maintenance costs. A real-life installation would likely consist of one main energy source type combined with a battery.

The modular concept for M/S Module is presented in figure 1 below. The module locations in the figure are positioned to highlight the possibilities to use both Lift On Lift Off (LoLo) and Roll On Roll Off (RoRo) energy modules.

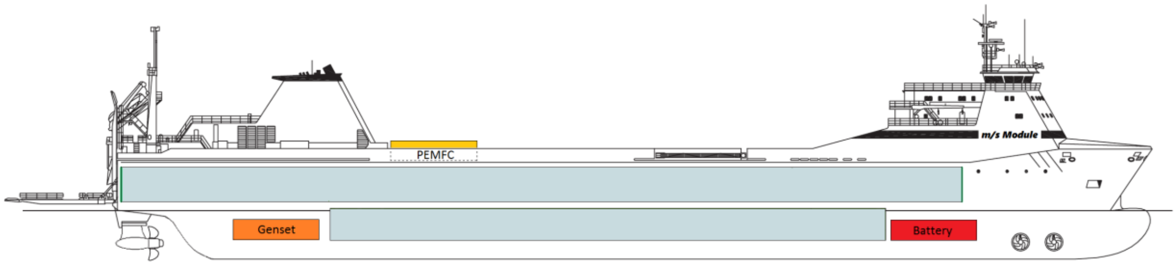

Figure 1. Example vessel m/s Module with energy modules

The example vessel (m/s Module);

Costal RoLo container vessel

LOA 150 m

Cruising speed of 17 knots

Electric propulsion, Steerable pods of 5+5 MW

Bow thrusters 2x0,8 MW

Auxiliary load of 200 kW

Accommodation and reefer load of 1 MW

2.2 Energy Sources

Today a vast majority of the worlds fleet is powered by fossil fuels such as Heavy Fuel Oil (HFO) and Marine Gas Oil (MGO) (DNVGL, 2019). As the climate pollution restrictions tighten, a variety of alternative energy sources enter the market. There is however an uncertainty of which energy sources will dominate the future of shipping. To cope with the continuously evolving situation, a modular concept with optional energy sources is presented. As the energy sources are converted to electricity, different energy sources can relatively freely be mixed or alternated.

In this thesis, the electrical grid's suitability has been investigated with Gensets, Proton Exchange Membrane Fuel Cells (PEMFC) and NMC batteries. The basic principle of the energy sources is presented in sections 2.2.1-2.2.3.

2.2.1 Genset

Internal combustion engines (ICE) are the by far most common source of energy on today's ships, both for providing energy to propulsion and for auxiliary power needs (DNV, 2020). An ICE is a heat engine that can depending on engine setup and auxiliary equipment run on a variety of fuels such as heavy fuel oil (HFO), Light Fuel Oil (LFO), Liquid Bio Oil (LBO) or Liquid Natural Gas (LNG). Alternative fuels for ICE's, such as Methanol from black liquor, Hydrogen from water and Ammonia, are also proposed as alternatives to cut the airborne CO2 emissions from the marine industry. (DNVGL, 2019.)

A Genset consists of a generator driven by an ICE. A typical source of auxiliary power for a ship consists of a number of Gensets. A setup with multiple Gensets is also used in solutions with electric propulsion motors.

For the Genset module in this thesis, the Wärtsilä W16V14 ICE combined with a Permanent Magnet (PM) generator from ABB has been chosen. The rated continuous electrical output from the Genset is 1155 kW_e @ 1800rpm (60 Hz). The Genset in this example is fueled by Light Fuel Oil (LFO). The technical specifications of the Genset are presented in Appendix 1.

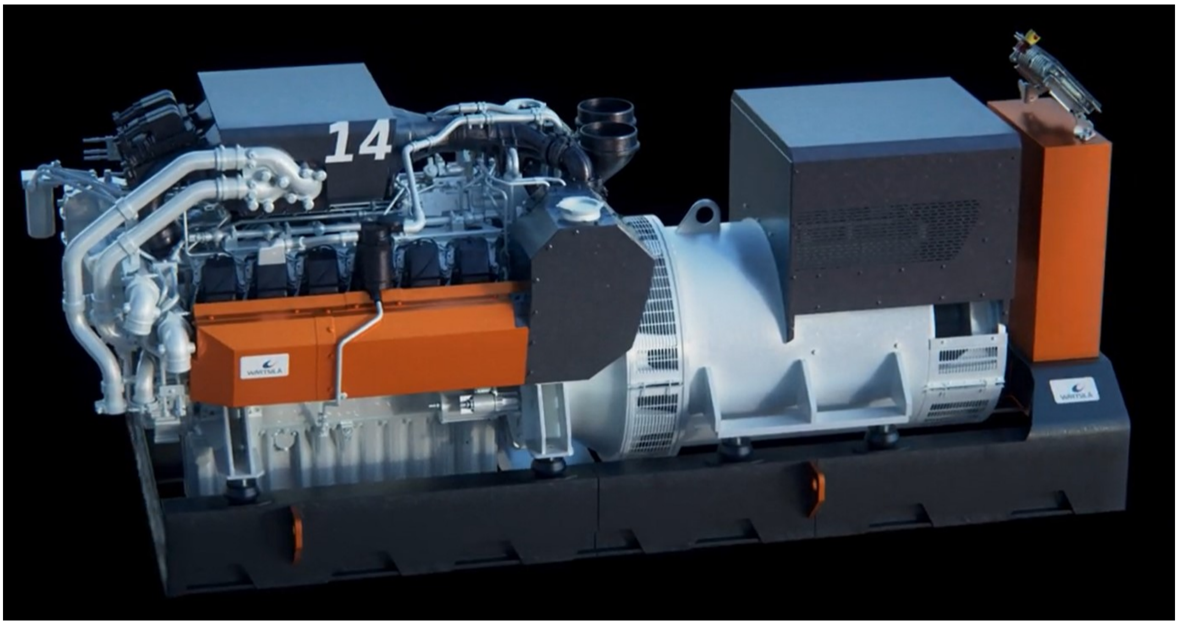

Figure 2. Wärtsilä 12V14 Genset (Wärtsilä, 2021)

The Specific Fuel Oil Consumption SFOC [g/kWh] of an ICE is mainly depending on engine load level, load variations and type of fuel. The typical optimal load range of an ICE is above

75% according to (Habermaas & Thurner, 2020). ICE´s are tuned according to emission restrictions, such as Tier II or Tier III depending on the traffic area, instead of the optimal SFOC. One method to reduce emissions and improve a Genset SFOC is to use a hybrid solution with a parallel connected battery for peak-shaving and spinning reserve. The load peaks are supplied by the battery whereby the Genset load is stable. By utilizing the spinning reserve of the battery, the amount of parallel connected Gensets can be reduced, thus raising the load of the remaining connected Gensets to a more optimal range.

Another method to improve the Genset SFOC is to use a variable speed solution, a solution where the optimal speed setpoint can be kept over the whole engine load range. The variable speed Gensets have traditionally been adopted only in combination with Direct Current (DC) grids as the Genset frequency varies with the rpm. In this study, the variable speed benefits are also utilized for the AC grid solution. Figure 3 below presents the potential fuel saving by a variable speed solution compared to a fixed speed solution.

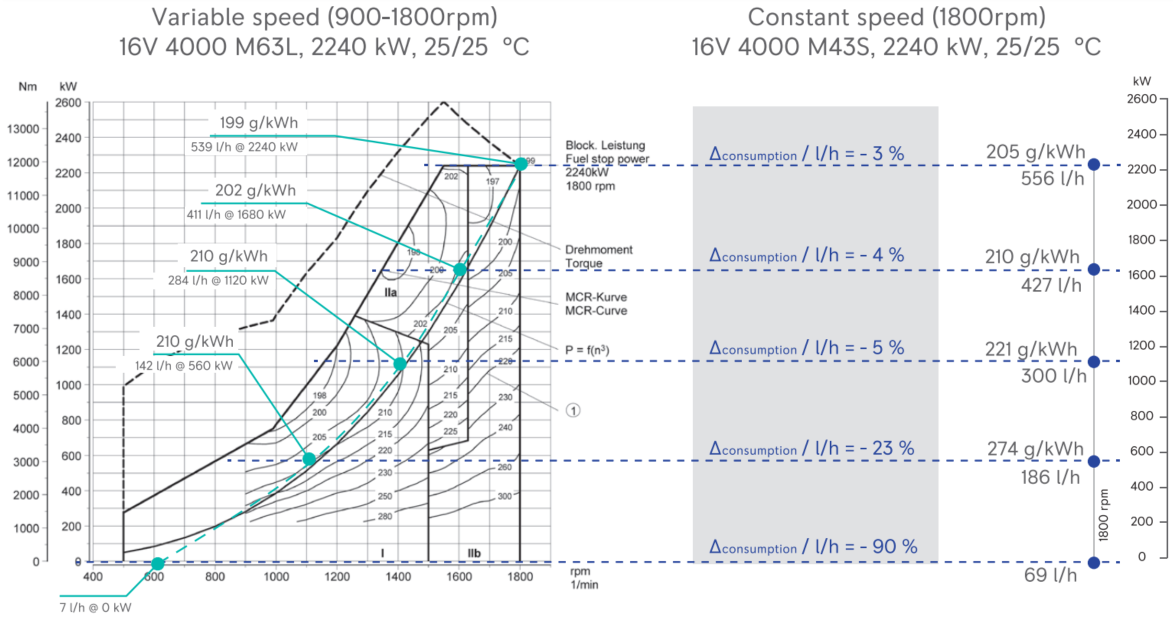

Figure 3. Variable vs. fixed speed Genset SFOC (Habermaas & Thurner, 2020, p. 3)

A Permanent Magnet (PM) generator has been chosen for the Genset in this thesis due to higher efficiency compared to the traditional synchronous generator (SM). PM motors and generators typically have 2-4 % less losses at full load, and 10% less losses at part load. This increased efficiency is achieved by the absence of rotor current and exciter losses as well as reduced winding losses. (Puranen & Parpala, 2019.)

The combination of a variable speed Genset and a PM generator results in an rpm dependent output voltage of the Genset. The Genset minimum speed has in this thesis been limited to 1350 rpm, which corresponds to a grid frequency of 45Hz. The Genset Load vs. output voltage relation is presented in figure 4 below. The variable speed solution benefits of improved SFOC, but correspondingly adds to the complexity of the Power Management System (PMS). The PMS is further presented in section 4.2.

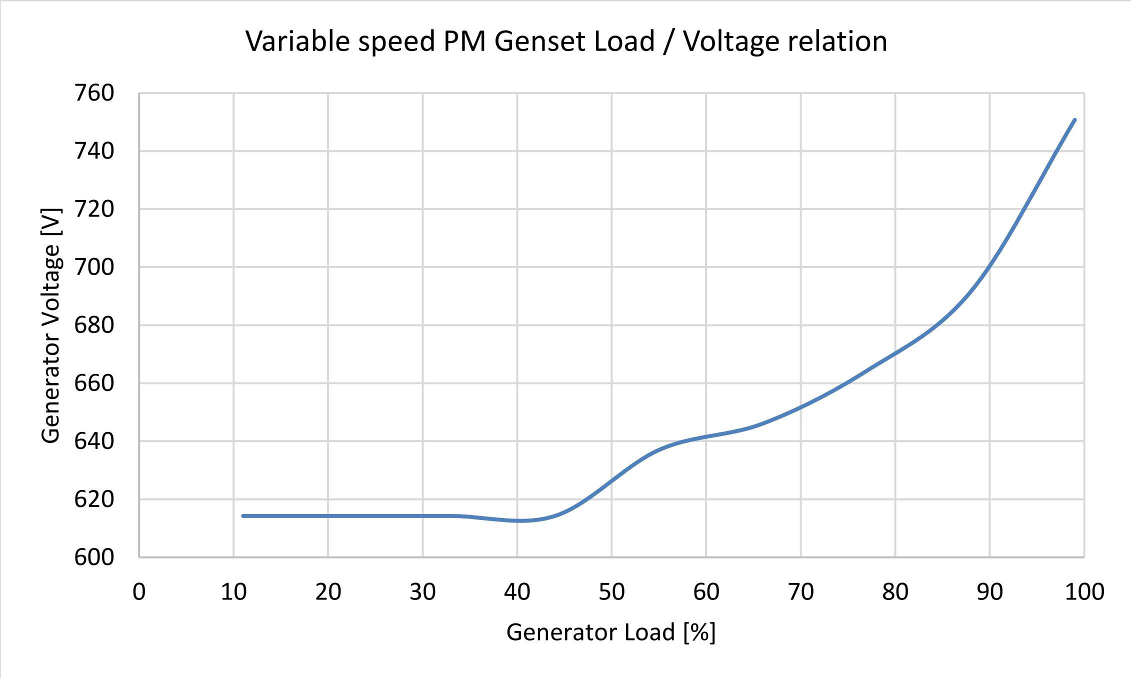

Figure 4. Variable speed Genset with PM generator – load vs. output voltage relation

2.2.2 Fuel Cells

A fuel cell is an electro chemical device that converts the chemical energy of a fuel and an oxidant into electricity and excess heat. The emissions from a fuel cell are dependent of the used fuel. The most promising technologies for marine applications today are Proton Exchange Membrane Fuel Cell (PEMFC), High Temperature Proton Exchange Membrane Fuel Cell (HT-PEMFC) and Solid Oxide Fuel Cell (SOFC) (Bogen & Jensen, 2020).

Fuel cells are being developed as alternatives for ICEs to provide vessels with energy for both auxiliary consumers as well as for main propulsion in an electric propulsion setup. Fuel cells are developed both in the kW and MW range. The key benefit of the fuel cell is higher efficiency than ICEs. The efficiency for producing electricity is typically in the range 33-35%, for a Genset, whilst PEMFC fueled with pure hydrogen can reach an electrical efficiency of 60% (U.S. Department of Eenrgy, 2021).

As this thesis focuses on the design of the electrical grid, only the PEMFC has been chosen for further investigation. The PEMFC uses pure hydrogen as fuel in addition with oxygen as the oxidant. The PEMFC investigated in this thesis is of type Ballard FCwave^{TM}. The unit output is 200 kW, whereby 15 pcs of parallel connected units have been used to reach the module power output of 3 MW. The datasheet of the PEMFC module is presented in Appendix 2.

The PEMFC consists of an anode and cathode, separated by an electrolyte. A visualization of the working principle is presented in figure 5 below. The electrons freed from hydrogen on the fuel cell anode side are led through an external electrical circuit to the cathode side, thus converting the chemical energy to electricity. The hydrogen ions travel to the cathode side via the electrolyte membrane. (Fuel Cell Works, 2021.)

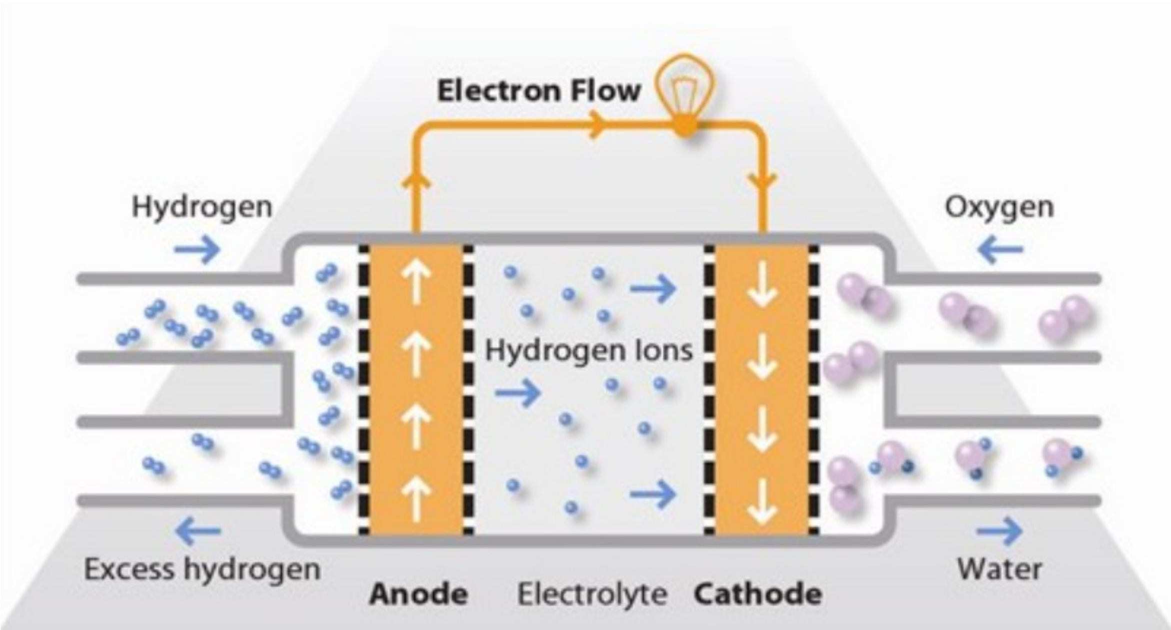

Figure 5. Basic principle of PEMFC (Fuel Cell Works, 2021)

The chemical reaction taking place in an PEMFC are presented below (Xing;Stuart;Spence;& Chen, 2021).

Anode side: $2H_2 \rightarrow 4H^+ + 4e^-$

Cathode side: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

A more practical solution principle of the PEMFC is presented by (Nikiforow, Pennanen, Ihonen, Uski, & Koski, 2018, p. 32) and is seen in figure 6 below. The hydrogen is led to the PEMFC stack via a pressure reducer (PR), a particle filter (FL), ejector primary pressure control (EPC) and the ejector (E). Excess hydrogen is led to the gas-liquid separator (S) from where the gas is re-used and the liquid is led from the process via a solenoid valve (SV).

The oxidant, ambient air is led to the PEMFC stack via a particle filter (FL), a gas blower (B), a membrane humidifier (MH).

The PEMFC stack is cooled by a liquid pump (P) circulating the coolant via a heat exchanger (HEX). The cooling circuit also includes a de-ionizing filter (DI) and an expansion tank (ET).

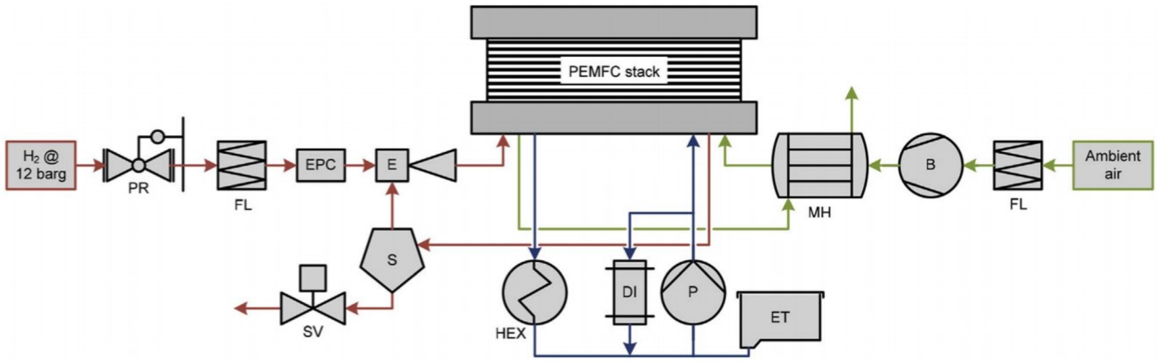

Figure 6. PEMFC with auxiliary equipment (Nikiforow, Pennanen, Ihonen, Uski, & Koski, 2018, p. 32)

The output of the fuel cell, despite of type used, is DC-voltage. The typical characteristics of the correlation between load and output voltage for an PEMFC is seen in figure 7 below (Zakis, Vinnikov, Roasto, & Strzelecki, 2010, p. 33). As the PEMFC is loaded, the output voltage drops thus contributing to a higher output current for the requested power out take.

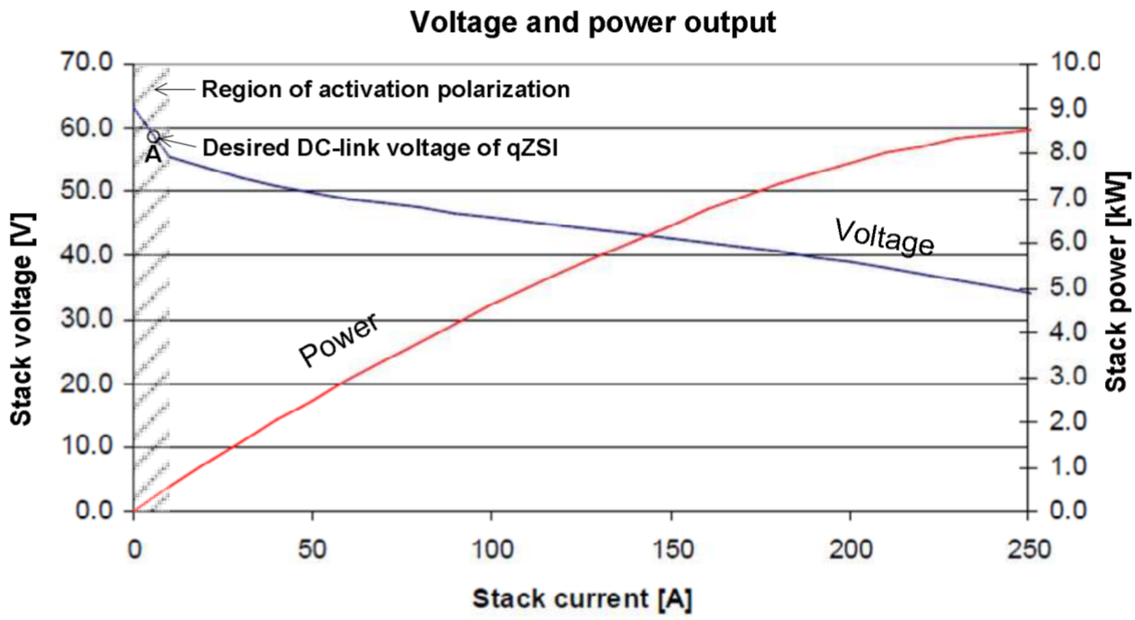

Figure 7. Typical fuel cell load vs. output voltage relation (Zakis, Vinnikov, Roasto, & Strzelecki, 2010, p. 33)

As the voltage of the PEMFC varies depending on load, and degrades during the life cycle of the fuel cell, the voltage must be stabilized and raised to the correct level for use in a grid with parallel connected energy sources. The operating voltage of the Ballard FCwave PEMFC drops from 720 V to 350 V during the load increase from 30 kW to 200 kW.

Hydrogen as a fuel requires safety precautions as it has a wide range of flammable concentrations in air. The required ignition energy is also lower than for gasoline and natural gas. Therefore hydrogen installations need components such as double-wall piping, safety valves, automatic shut off valeves, gas tight valve units and both enclosure specific and shipwide leakage detector systems. Fuel cell installations are classed as hazardous areas (ABS, 2020, p. 33).

2.2.3 Batteries

Batteries onboard vessels can be utilized in many different ways. Examples of existing solutions are main source of energy for All Electric Ships (AES) for short voyage solutions, spinning reserve to reduce amount of running Gensets, peak-shaving to stabilize the load of Gensets and Fuel Cells, and as the main source of energy for sensitive areas of a longer voyage.

The batteries in this thesis are used for peak shaving and spinning reserve for the costal and deep sea Genset and PEMFC solutions. The batteries are also investigated as the main energy source in the pure battery solution for short sea operations.

With the implementation of large battery packs, safety becomes critical. Depending of the used battery chemistry, the risk level varies. The tradeoffs between some of the Lithium battery chemistries are presented in figure 8 below (Saldaña; San Martín;Zamora;Asensio;& Oñederra, 2019).

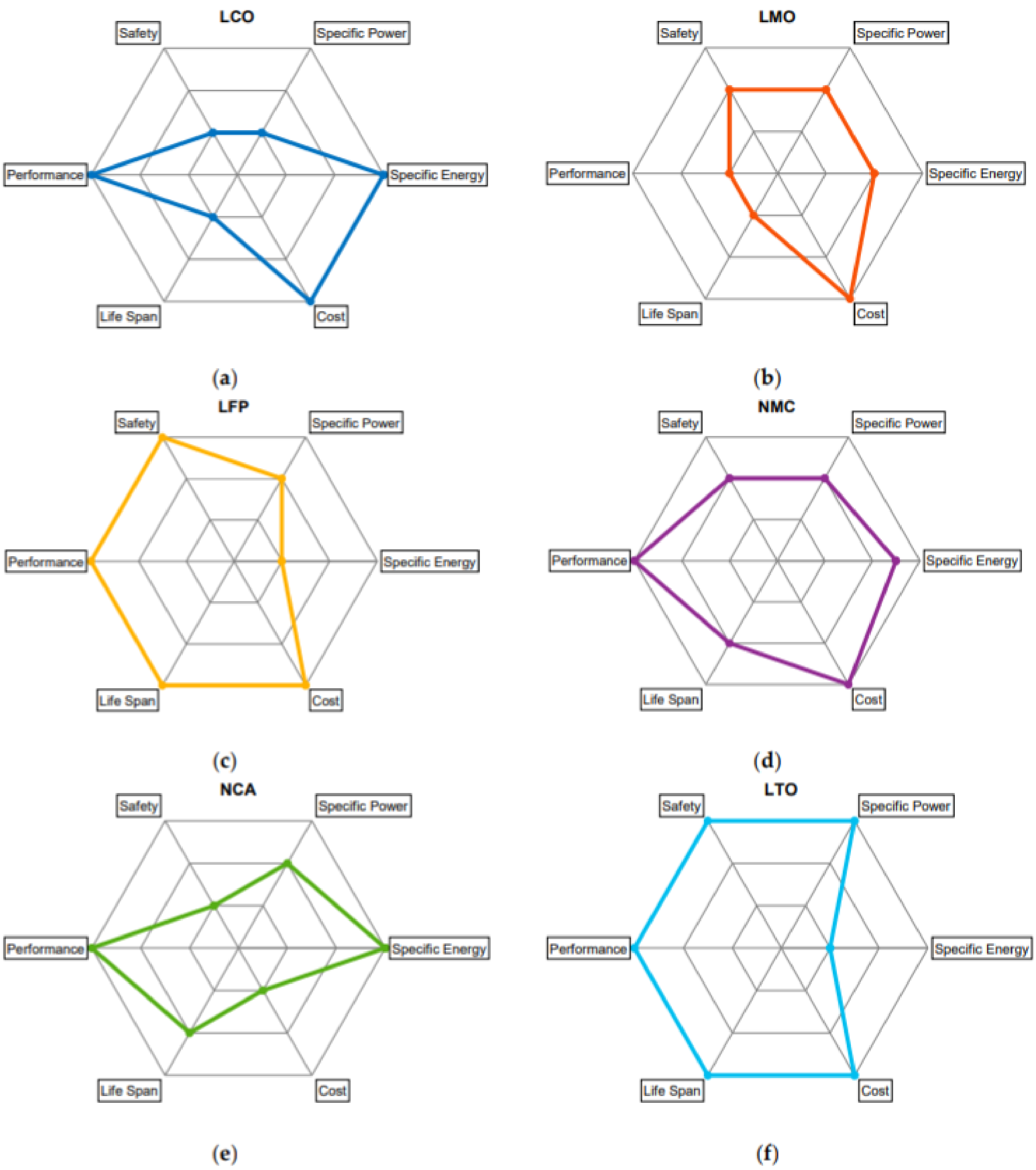

Figure 8. Lithium battery chemistry characteristics

Today, several used Lithium battery chemistries are suffering from a risk of thermal runaway, a chain reaction caused by overheating of a battery cell. The overheating causes flammable gases to be released, which can if uncontrolled, lead to an extremely hazardous fire. The battery string or the whole pack with a faulty cell must immediately be disconnected and isolated both electrically and thermally from healthy cells to prevent the risk of thermal runaway. The flammable gases must be lead out in an controlled way, through a path without the risk of ignition. Spaces with large Lithium batteries are classed as hazardous areas (ABS, 2020, p. 33) and must thereby be equipped with suitable fire extinguishing systems such as direct foam injection or high pressure water mist (DNV GL, 2019, p. 3).

As battery fires are extremely hazardous, the main focus of battery safety lies within prevention of thermal runaway. The battery is equipped with a Battery Management System (BMS). The BMS measures battery voltages and temperatures on an individual cell level. The tasks of a BMS are according to (MAN Energy Solutions , 2019);

- Overload prevention
- Ensure safe charging/discharging
- State Of Charge (SOC) monitoring
- Cell SOC leveling
- Calculation of power limits for ship's Power Management System (PMS)
- State Of Health (SOH) monitoring
- Triggering of battery system preventive and Condition Based Maintenance (CBM) alarms
- Disconnection of faulty cells or modules
- Activation of battery module internal safety systems
- Control of battery unit cooling system via Thermal Management System (TMS)

To evaluate the electrical grid types, an existing containerized battery solution has been used as the foundation for the battery module in this thesis. The column for *40 ft. High Cube Container* in Appendix 3 presents the specifications of this *Shift 2 Clean Energy* containerized solution. The module uses Lithium Nickel Manganese Cobalt Oxide (NMC) chemistry and has been modified to 4 MWh in this thesis. The modification is described in section 5.2.3.

3 Electrical Grid AC vs. DC

The vast majority of the existing world fleet has an AC grid with either 50 Hz or 60 Hz fixed frequency. The different voltage levels, for example, 690 V for motors, 400 V for galley equipment and 230 V for accommodation are achieved via transformers.

However, keeping a fixed frequency has a negative impact on the vessel's operational costs (OPEX) if Gensets are used for electricity production. As presented earlier in section 2.2.1, Gensets benefit of a variable speed solution as the specific fuel oil consumption SFOC [g/kWh] is significantly improved, especially at low loads.

By using a DC grid, the speed of a Genset is allowed to vary, thus improving the SFOC. The AC grid investigated in this thesis is of untraditional, variable frequency type. The grid frequency is allowed to vary in the range of 45…55 Hz, which allows also the AC grid to benefit from the improved SFOC empowered by variable speed Gensets.

The main reason of choosing an AC grid over DC is the fact that an AC-grid has traditionally had lower CAPEX costs than the DC-grid. Another factor is the better availability of standardized parts for the AC-grid, not to forget that most domestic and end user equipment is only available as AC versions.

A comparison of grid types is always case specific. But a general comparison of the pros and cons of a traditional AC and a DC grid are presented by (Jin, et al., 2016) and are listed in table 1 below. The table has been extended to involve the variable speed AC grid by the writer.

Table 1. General comparison of grid types

	Fixed AC	*Variable AC*	*DC*
Synchronization	Voltage, Frequency, Phase Angle	Voltage, Frequency, Phase Angle	Voltage
Reactive Power	Increased component dimensioning	Increased component dimensioning	No affect
Harmonics	Need to be considered	Need to be considered	No affect
Voltage Level Adj.	Bulky Transformers	Bulky Transformers + Power Electronics	Compact Power Electronics
Parallel DC Energy Sources	Power Electronics + Transformer	Power Electronics + Transformer	Power Electronics
Short Circuit Current Capacity	Good Level	Limited due to Power Electronics	Limited du to Power Electronics
CAPEX	Low	High	High
OPEX	Highest	Lower	Lowest

3.1 Investigated AC Grid

The investigated variable frequency AC grid is presented in figure 9 below and in bigger scale in Appendix 4.

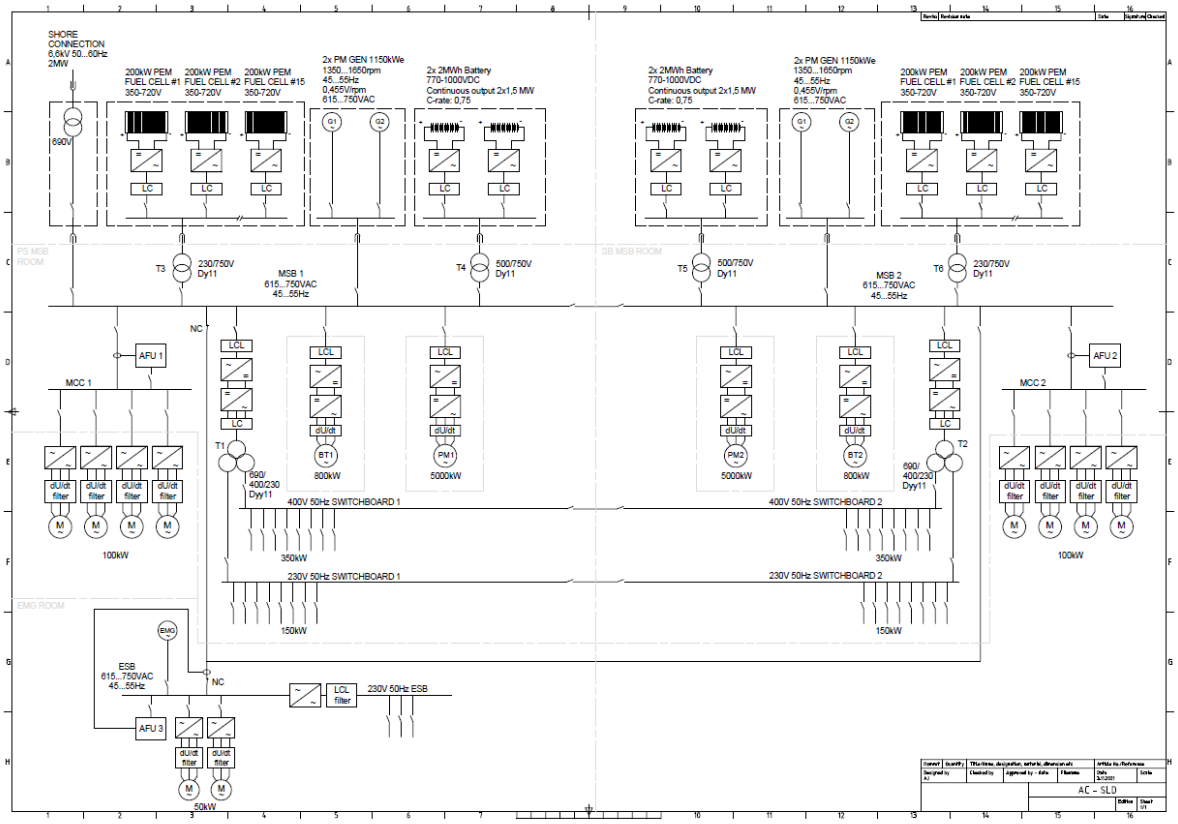

Figure 9. m/s Module variable frequency AC-grid

A traditional AC grid has a fixed voltage, and a fixed frequency of either 50 Hz or 60 Hz. For example, 690 V 50 Hz is a commonly used main voltage of a 150-200 m ship´s Main Switch Board (MSB). In this study however, the MSB voltage is allowed to vary in the range of 615…750 V, and the frequency in the range of 45…55 Hz, thus enabling a combination of a variable speed Genset and a PM Generator. The benefit of variable speed is lower specific fuel oil consumption (SFOC) [g/kWh], and the benefit of the PM Generator is improved efficiency compared to a traditional synchronous generator.

The range 45…55 Hz has been chosen as 45 Hz is the minimum frequency for Danfoss Vacon NX series converters according to datasheet. 55 Hz (1650 rpm) comes from the SFOC & torque curve for the Wärtsilä 16V14 in Genset use. The curve shows that the Genset can be loaded at 1150 kW (maximum continuous load) with sufficient torque margin at 1650 rpm where the SFOC is lower than at 1800 rpm. The Genset voltage varies as a Permanent

Magnet generator has been chosen for this thesis. The Voltage-Speed relation for the generator is 0,455 V/rpm.

According to Danfoss (Personal communication with Product Manager, Premium Drives 30.3.2021), the 45 Hz is not an absolute minimum input frequency for the NX series converters. Also, the input voltage for the converters is allowed to go as low as 553 VAC. With these factors optimized, a somewhat wider voltage and frequency window could be used. This would lead to further improved SFOC at loads below 30% for the variable frequency AC solution.

The voltage sensitive domestic equipment in this solution are connected to stable voltage levels of 400 V 50 Hz and 230V 50 Hz via variable frequency drives (VFDs) supplying transformers T1 and T2. The switching frequency for the domestic consumers are chosen to 3,6 kHz which minimizes the harmonic distortion of the output.

The auxiliary equipment, such as pumps and fans are connected to the grid via Variable Frequency Drives (VFDs) to reach the minimum, and thereby the most economical speed required by each process. Significant energy savings can be achieved as the relation between speed and energy consumption is cubic for centrifugal pumps and fans according to the affinity law presented in formula 1 below.

$$P_2 = P_1 * \left(\frac{N_2}{N_1}\right)^3 \quad (1)$$

Where

P_1 = Power old [kW]

P_2 = Power new [kW]

N_1 = Rotation speed old [rpm]

N_2 = Rotation speed new [rpm]

In both the AC and DC grid solutions, the vessel’s energy sources consist of six energy modules, three connected to the port (PS) side grid and three to the starboard side grid (SB). As the focus of this thesis is to compare the grid suitability for the modular concept with replaceable energy modules, a number of different energy sources has been investigated. In an implemented solution, a likely scenario is to have one main source of energy combined with a battery. For instance, a combination of Gensets and a battery or fuel cells and a battery. The grid suits also for a pure electric solution with only battery modules.

Within the investigated solution, the main sources of energy are the Genset and PEMFC modules. The battery works as a peak shaver, a spinning reserve and a booster in the rare occasions when full power is needed. Additional energy modules can be added to the grid in case a higher power level is needed.

3.2 Investigated DC Grid

The investigated DC grid is presented in figure 10 below and in bigger scale in Appendix 5.

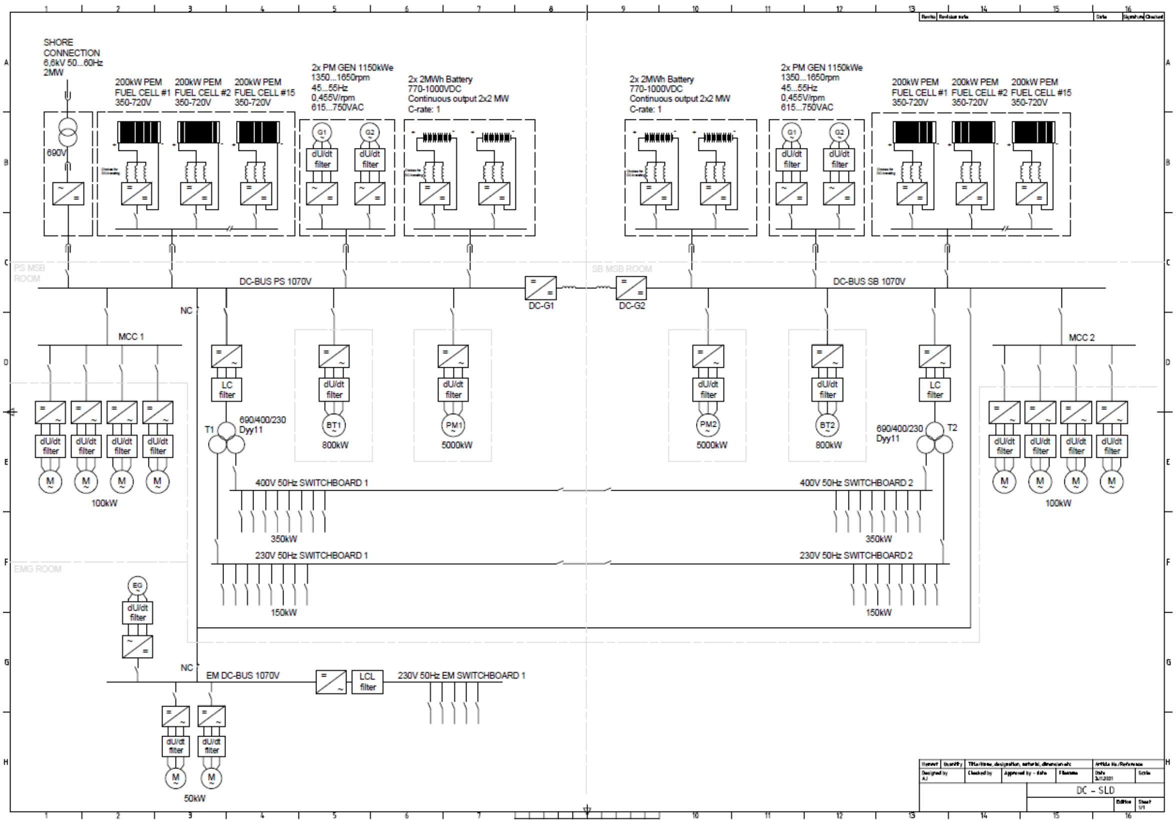

Figure 10. m/s Module DC-grid

The DC solution has a main bus voltage of 1070 VDC, highest allowed for the studied Danfoss/Vacon NX converters in this thesis. The 45…55 Hz and 615…750 V Genset voltage is filtered, boosted and rectified before reaching the bus. The generator voltage varies as Permanent Magnet generators (PM) have been used. For comparison reasons, the same Genset has been used for both the variable AC grid and the DC grid.

The 720…350 V DC voltage from the PEMFCs is boosted with help of chokes to the required level of 1070 V by the DC/DC converters. The same DC-boost function has been used for the battery modules, where the 1000…770 V battery voltage is boosted to the required level of 1070 V.

3.3 Power Quality in AC Grid

The main quality factors for an AC grid are Voltage level, Frequency stability, Total Harmonic Distortion (THD) and Electromagnetic Interference (EMI). Also, a good insulation level is an important criterion of a healthy grid.

3.3.1 Voltage and Frequency

Firstly, about the voltage and frequency variations. The required quality of a ship voltage and frequency are defined in the classification society rules, unless the equipment supplier or the national or international rules require a higher quality. The purpose is to ensure the satisfactory operation of the connected equipment. In this thesis the values listed in table 2 below have been used as guidelines.

Table 2. Allowed voltage and frequency variations (ABS, 2016, p. 687)

Voltage and Frequency Variations for AC Distribution Systems		
Quantity in Operation	*Permanent Variation*	*Transient Variation (Recovery Time)*
Frequency	±5%	±10% (5 s)
Voltage	+6%, –10%	±20% (1.5 s)

In the case of the variable frequency AC grid investigated in this thesis, the MSB voltage and frequency are allowed to vary more than allowed in table 2 above. However, as the MSB voltage is only used for propulsion purposes and are within the required levels set by the converter manufacturer, whilst the sensitive accommodation equipment is supplied via stabilizing converters. Therefore, the exceeding of the allowed voltage window should not be a problem. Nevertheless, it is a design factor that needs to be verified by the classification society at design stage.

3.3.2 Total Harmonic Distortion (THD)

Harmonics in AC grids is a result of non-linear loads taking non-sinusoidal current from the grid which results in distortion of the supplying voltage. Typical sources of harmonics onboard vessels are power electronics, rectifiers of variable speed drives, LED- and fluorescent lighting.

An increased level of harmonics causes excessive losses in cabling, as the resistance increase with the frequency due to skin and proximity effect, and in electric motors mainly due to excess losses in windings. The highest derating factors due to harmonic distortion is however found in transformers. Every grid design is very case specific, but to give an understanding of the weight of the additional losses caused by harmonic distortion, oversizing factors of 5-7% for cabling, 1-1,5% for induction motors and 7-19% for transformers are used in an untreated AC grid with purely Pulse Width Modulated (PWM) converters as load. The need of oversizing decreases however approximately with the square of the load current distortion. For example, if the load consisted of only 50% of PWM converters, the need for transformer oversizing would decrease from 19% to 4,5% (Lehtonen, 1996, p. 12). Harmonic distortion can also disturb sensitive equipment, such as energy source protection relays, if voltage notching, in other words excessive AC voltage zero crossings occur.

The sum of the harmonic voltages, THDv, must be kept at maximum 8% at the Main Switch Board on a vessel (ABS, 2016, p. 674). The relation between voltage distortion V_d and current distortion I_d, are dependent on the source impedance Z_d according to Ohm´s law. The relation is presented by formula 2 below. The equation shows that a higher source short circuit impedance results in higher Voltage distortion.

$$V_d = I_d * Z_d \qquad (2)$$

Generators typically have an impedance level of 18-20% compared to a transformer of typically 5-6% (Eaton, 2021). This shows that the THD level in the modular AC grid will vary depending on the used energy sources. With the used setup where most of the converters have Active Front End rectifiers (AFE), this do not need to be compensated for as the THD level is generally on a low level.

There are several methods to mitigate harmonics in an AC grid. The main harmonic mitigation method for the variable frequency AC grid is the use of Active Front End rectifiers (AFE). The AFE in combination of the LCL filter is resulting in a current distortion level THDi in the range of ~3% (ABB, 2019). To compare the AFE performance, (Hartmann, 2016, s. 3) gives the THDi value of a classic 6-puls diode bridge with AC Chokes to be near 48%.

As the writer was not able to find 690 V AFE Low Harmonic Drives in the power range of 2-30 kW on the market, the harmonic mitigation method for the converter controlled auxiliary pumps and fans connected to the MCC-switchboards is done by Active Filter Units (AFU). The AFU measures the distortion of the incoming supply to the MCC, and if needed, injects a current with a 180-degree phase shift to cancel out the problematic parts of the main supply current. The auxiliary load of the investigated vessel can be up to 30% of the total load in harbor. As this is a significant amount, if untreated, these traditional 6-pulse rectifiers could not be used.

3.3.3 Common Mode Current and Electromagnetic interference (EMI)

The star point to ground voltage varies in a VFD controlled motor. This Common Mode Voltage changes as the Pulse Width Modulated (PWM) output voltage from a frequency converter is unsymmetrical. The jumping star point voltage drives a high frequency current via stray capacitances in cabling and motor winding to motor chassis, or any other stray capacitances, and thereby emit EMI. Measures to minimize stray capacitance is to use high quality motors and most importantly high-quality cables. EMI from VFD to motor cables is effectively blocked by using of screened cables. Figure 11 below shows example of common mode current paths via stray capacitances.

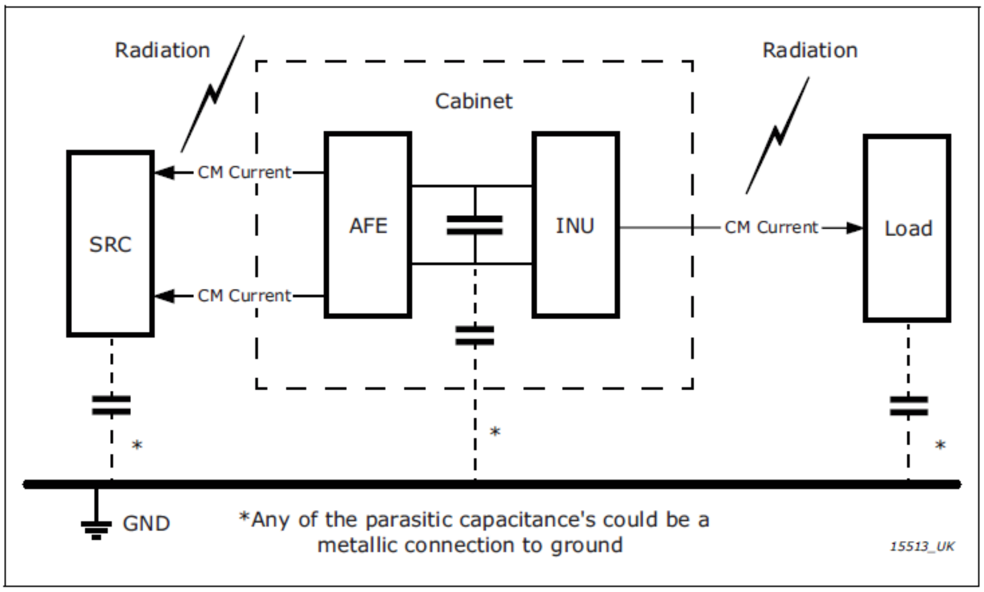

Figure 11. Common mode current paths (VACON, 2020, p. 34)

3.3.4 Insulation Monitoring

A ship's AC grid is often built floating, a so-called IT-grid. This grid is tied to ground (ship's metallic hull) only by stray capacitances. For instance, a healthy 690 V IT-grid have 400 V between each phase and ground. The main advantage of the IT-grid is that the first earth fault do nota blow a fuse, instead the crew is notified by an insulation monitoring system alarm and have time to locate and repair the earth fault. In case of two separate firm earth faults, if located in separate phases, results in a blown fuse. The IT-grid has proven its suitability to keep essential systems operative in a continuously vibrating environment.

Special notice must be paid when choosing the insulation measurement device for an AC or DC grid with numerous frequency converters. The equipment needs to be able to differentiate between the high frequency common mode currents and true earth faults within the 45…55 Hz frequency range.

3.4 Power Quality in DC Grid

The main quality factors for an DC grid are Voltage level, Ripple, oscillating currents and voltages, Electromagnetic Interference (EMI) and Common Mode Voltage.

3.4.1 Voltage

The voltage tolerance window accepted by American Bureau of Shipping (ABS) is presented in table 3 below and have been used as guideline for the DC-Grid solution in this thesis. The DC bus voltage is kept steady at 1070V in the investigated solution. The voltage ripple on the DC side is minimized by sufficient DC capacitors dimensioned by the converter manufacturer. Big DC capacitors introduces the demand of pre-charging circuits to limit the inrush current.

Table 3. DC grid quality demands (ABS, 2016, p. 687)

Voltage Variations for DC Distribution Systems (such as systems supplied by DC generators or rectifiers)	
Parameters	*Variations*
Voltage tolerance (continuous)	±10%
Voltage cyclic variation deviation	5%
Voltage ripple (AC r.m.s over steady DC voltage)	10%

Voltage Variations for Battery Systems	
Type of System	*Variations*
Components connected to the battery during charging (see Note)	+30%, –25%
Components not connected to the battery during charging	+20%, –25%

3.4.2 Oscillating currents

A DC grid do not experience traditional AC-grid harmonic distortion, as harmonic distortion is defined as the ratio of harmonics compared to the fundamental frequency. As the harmonics are multiples of the fundamental frequency, which for a DC grid is 0 Hz, the multiples are also 0 Hz. However, DC grids can experience a similar phenomenon with oscillating voltages, and thereby oscillating currents, between parallel connected power converters connected to a common DC-bus. These oscillating currents cause excess losses and stress on the equipment. Primary mitigation method for the problem is correct converter parametrization, which enables a stable load sharing. (Whaite, Grainger, & Kwasinski, 2015.)

3.4.3 Common Mode Voltage and Electro Magnetic Interference

Common Mode Voltage is a jumping star point voltage towards ground in an AC motor supplied by a VFD. The jumping star point voltage is caused as the Pulse Width Modulated (PWM) output from the VFD is not symmetrical. The Common Mode Voltage can disturb sensitive equipment such as battery management systems, as the DC grid including the battery management system, is connected to the ship´s hull via stray capacitances. The Common Mode Voltage also cause High Frequency Common Mode Currents via stray capacitances, these currents again cause disturbance in form of Electromagnetic Interference (EMI).

To minimize common mode issues in DC solutions, the DC+ and DC- potentials are connected towards the ship hull by means of High Frequency (HF) capacitors, a stabilizing method called Common Mode Ballasting. The principle is presented in figure 12 below. Common Mode Ballasting results in a stable "clean" DC side, and a "dirty" AC side where the common mode voltage is allowed to rotate freely in transformers or electric motor star points. The HF capacitors should be dimensioned significantly bigger than the total system stray capacitance (VACON, 2020). Due to the modular energy module approach in this study, each energy module is equipped with built in Common Mode Ballasting Capacitors.

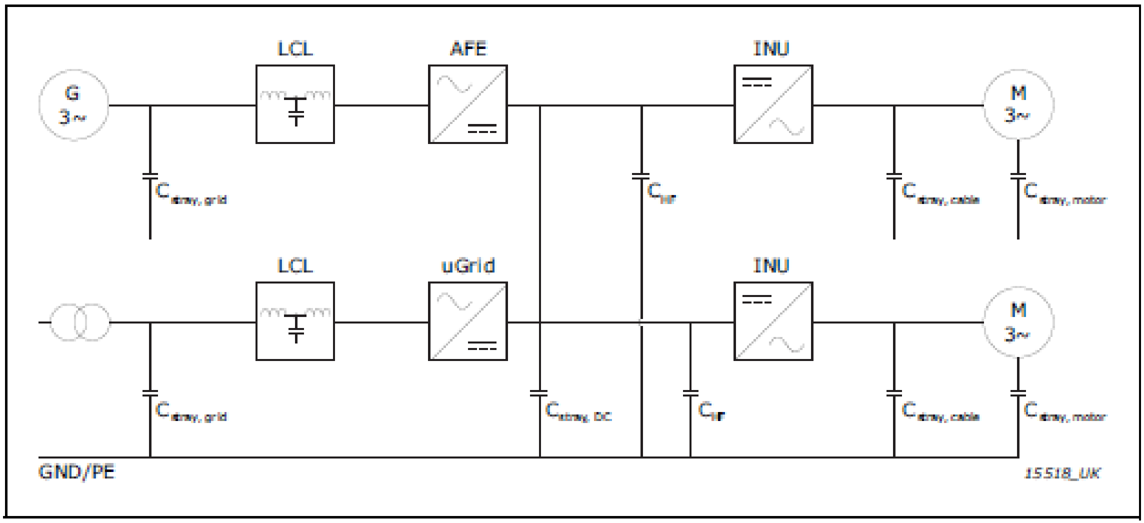

Figure 12. HF capacitors on common DC link (VACON, 2020, p. 37)

3.5 Protection and selectivity

3.5.1 AC-Grid

The protection requirements for a variable frequency AC grid are the same as for a traditional IT AC-Grid; short circuit protection, overload protection, insulation monitoring and energy source specific protection devices. Sensitive equipment may additionally have separate over-/under voltage relays and over-/under frequency relays.

The short circuit and overload protections are covered with standard components also used in traditional IT grids and onshore TN-S and TN-C grids, such as Busbar Circuit Breakers, Molded Case Circuit Breakers (MCCB) and fuses. Selectivity is ensured according to the same principles, by choosing and adjusting the protection devices by comparing their current versus trip time characteristics.

A worst-case fault, a busbar short circuit, needs special attention on the variable frequency AC grid, as the amount of available short circuit current varies depending of the used energy sources. A typical short circuit level I_{cu} from a converter is in the range of 1,5…3xI_n, which corresponds to a level of 3,6…7,3 kA for a 3000 kW PEM-FC. A Genset module with two direct online Gensets with a total power of 2300 kW gives out a short circuit current in the range of 10xI_n, corresponding to a value in the range of 20 kA. If the busbar short circuit occurs whilst supplied by converters, the supplying converters are switched off and the faulty half of the grid is isolated. If the busbar short circuit occurs whilst supplied by Gensets, the genset breaker, and depending of the short circuit location, possibly also the bustie breakers trip.

The 230 V and 400 V AC consumer grids in the solution are protected against overload and short circuit by traditional AC switchboard circuit breakers, MCCB´s and fuses. The protective components must disconnect all live conductors simultaneously. Personal protection is ensured by using Residual Current Devices (RCD) where applicable.

The accommodation load is supplied by stabilizing converter via transformers T1 & T2. The maximum short circuit current fed by this converter is limited to 937,5A, corresponding to approximately 2xI_n, which is a typical value of a semiconductor power supply. This low level of available short circuit current set high demands on both choosing and setting of circuit protection devices to ensure grid selectivity. In practice, preferably one brand of products is used, and the protection type used is desirably MCCB with adjustable trip points, as the availability of short circuit current for traditional fuse tripping is generally too low.

In the case of the accommodation load, the converter is primary not allowed to trip in case of a short circuit at the consumer end, as this causes unnecessary power shortages to other equipment. If selectivity is not reached by choosing suitable MCCBs, the converter feeding the 230 V and 400 V grids need to be over dimensioned to ensure a higher short circuit current level.

3.5.2 DC-Grid

Fault current protection devices used in an DC-Grid have a disadvantage compared to AC-grids. In the AC-grid, the current naturally cross Zero twice each period. In an DC-grid on the other hand, the current must be forced to zero, which lead to more complex and costly protection devices. Commonly used grid protection devices are controlled semiconductors, fuses and DC-breakers. Modern hybrid protection devices, such as DC-bustie breakers are often a combination of controlled semiconductors, fuses and disconnectors (Kim, Park, Roh, & Chun, 2018).

Overload conditions in the investigated DC-solution are primarily dealt with by the controllable converters. In case of a short circuit in an inverter output circuit, the inverter trips and isolates the fault. In case of an internal failure in a converter semiconductor circuit, the inverters are equipped with a secondary level of protection, consisting of DC-fuses, which are dimensioned to blow without causing failure within the parallel connected converter units.

Ensuring selectivity in a common DC system with several connected converters is although challenging. During a short circuit condition on the DC-bus, the fuses closest to the fault location burns, but so do often other, and not necessarily fuses near the fault location (Vacon, 2018, p. 3). During a DC-bus short circuit situation, short circuit current is fed by energy sources, energy storages, inverter unit's internal capacitors and AC-motors via converters (ABS, 2018, p. 11).

Figure 13 below presents a DC-bus short circuit (location #1), a energy source internal short circuit (location #2) and an consumer group short circuit (location #3). The short circuit handling of end consumer lines (location #4) were described earlier in section 3.5.1.

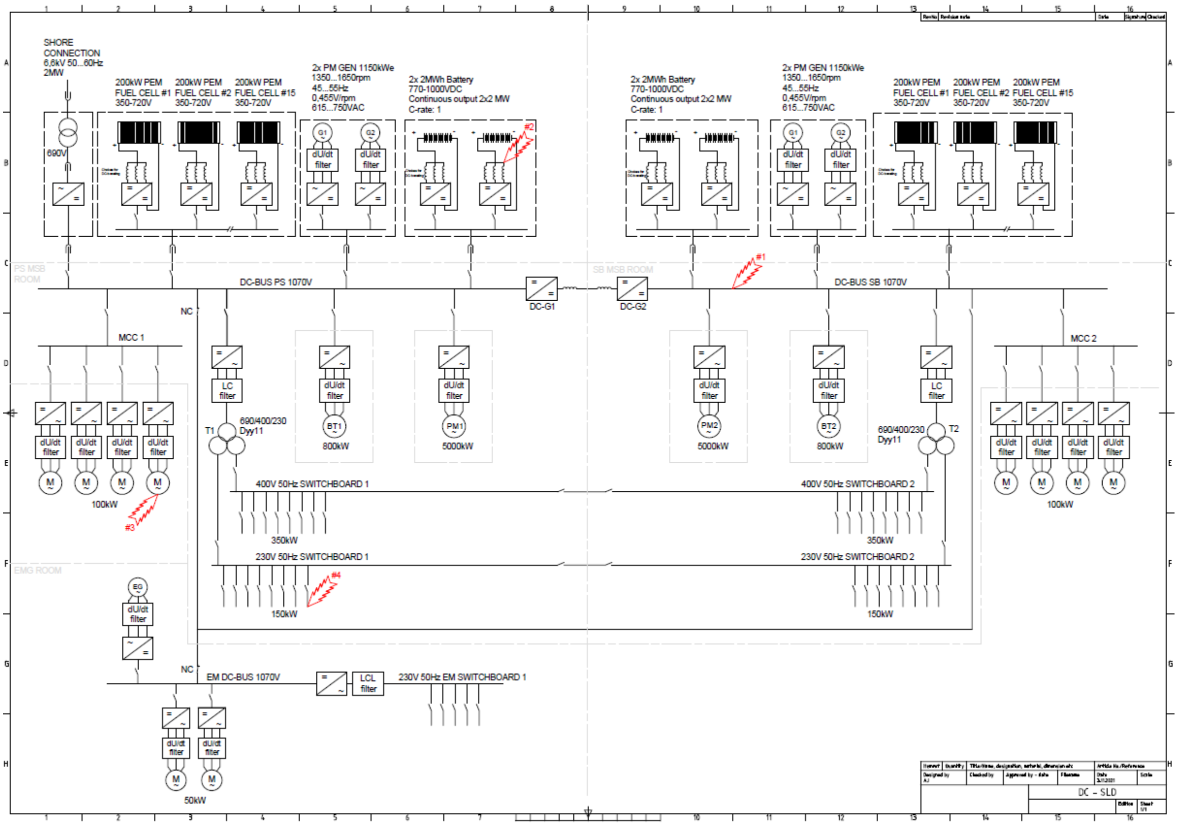

Figure 13. Short circuit example locations

To avoid a full black-out in an DC-bus short circuit situation (location #1), the healthy part of the DC-bus is separated in 4-150 µs by a semiconductor bustie breaker, fast enough to avoid device tripping due to low voltage on the healthy side of the DC-bus. The disconnection time of the DC-bus breaker is manufacturer dependent. The product investigated in this study is the VACON NXP DCGuard, with an tripping time of 100-150 µs.

In case of a short circuit within the energy source (location #2) the fault is isolated by the converter, and as a back-up, by DC-fuses upstream from the converter. The energy source internal protection devices shut off the fuel supply immediately to ensure a quick shutdown.

Further downstream from the DC-bus, in short circuit locations after the single load converters (location #3), each converter works as an overload and short circuit protection. Selectivity is ensured as the converter supplying the fault location trips and isolates the fault.

3.6 Redundancy

The level of redundancy of a ship's electrical grid is always a compromise between acceptable level and system cost, regardless of the chosen grid type. As the investigated vessel total power, including propulsion, auxiliary and accommodation loads are well above the 3MW level of SOLAS 74/78 Chapter II-1 (IMO, 2012, p. 101) the MSB is split into two sections. The divided bus is also required as the compared AC and DC grid solutions of this thesis are designed according to ABS R2-S class, where a single failure will reduce, but not compromise the propulsion and steering capability of the vessel. The design concept accepts failures to occur, but only one critical failure at a time, including fire or flooding of an engine room (ABS, 2016, p. 277).

The redundancy for both grid types are primarily relying on the spinning reserve from the batteries. Therefore, these hybrid systems are highly dependent of the battery capacity, and in the confidence of its accuracy to be able to carry the ship's electrical grid in case of a primary energy source disconnection (Hukins, 2021). Within the investigated grid types, both grid halves have own battery modules which further improve the redundancy.

The next level of improved redundancy is the multiple parallel, relatively low power modules. The risk of overloading the remaining units is small in case of a failure within an energy module.

The third factor contributing to an improved redundancy is the almost instantaneous synchronization of the converter-controlled energy sources. The converter controlled Genset in the DC-solution benefits of a quicker synchronization time in the range of 10 s compared to the directly connected AC Genset which synchronization time is typically in the range of 45 s.

The major benefit for the DC grid solution is the capability to handle busbar short-circuit situations in a softer way than the AC grid. The bus short circuit handling for the DC solution is fast enough to prevent a full black-out, which is a likely result of a bus short circuit in an AC-grid. With the risk of a total black-out, the bustie breaker of the AC grid is to be open when ABS R2-S level of redundancy is needed. The quick short circuit handling also reduces the voltage transients typical for AC grids in a short circuit situation. The voltage transients are likely to damage sensitive equipment.

Special notice must be paid, for both grid types, to common mode failures where redundancy is defeated due to all apparently separate and redundant systems react adversely to a common stimulus (Germanischer Lloyd, 2013, p. 2). Energy Storage Systems (ESS) and Uninterrupted Power Supply (UPS) installations often bring a lot of this unwanted commonality to vessel control systems through Power Management Systems (PMS), Energy Management Systems (EMS), instrumentation and communication networks (Hukins, 2021).

3.7 Synchronization

The synchronization of energy sources in an AC grid require matching of frequency, phase angle and voltage levels. For a DC solution, only matching of voltage is required. This gives the DC grid an advantage, as the synchronization can be done quicker.

For synchronization of generators in traditional AC grids, the frequency and voltage windows are reached quite quickly, but the matching of phase angle is time consuming. This is especially noticeable onboard ships where the grid is relatively weak. For instance, if bow thrusters are connected in a traditional AC grid, the synchronization of additional Gensets is often prohibited as the risk of phase angle mismatch due to rapid load changes exists.

For synchronization of the energy modules in this study, the need to lock the main thruster load while synchronization is necessary only for the direct online AC Genset. The synchronization of the converter-controlled energy sources is almost instantaneous.

3.8 Reactive Power

Reactive power is a problem of an AC grid and is the outcome of a phase shift between the voltage and current and is caused by the connected load. If the supply voltage is a pure sine-wave, only reactive power of the main frequency is flowing in the grid. The existence of reactive power in an electrical grid causes losses and require over dimensioning of components such as cables and transformers (ABB, 2000, p. 21). To minimize the reactive power need in the AC grid investigated in this thesis, Active Front End (AFE) converters has been used. These converters present power factors near 1 down to 40% load levels, see figure 14 below. The compared Matrix converter, an AC/AC converter without the DC-step, is not used in this thesis. For a traditional 6-pulse diode bridge, the power factor is close 1, regardless of the load level, but the 6-pulse diode bridge rectifiers again cause high harmonic distortion currents.

Due to the use of AFE converters, the design cos φ for the investigated AC grid is set to 0,95.

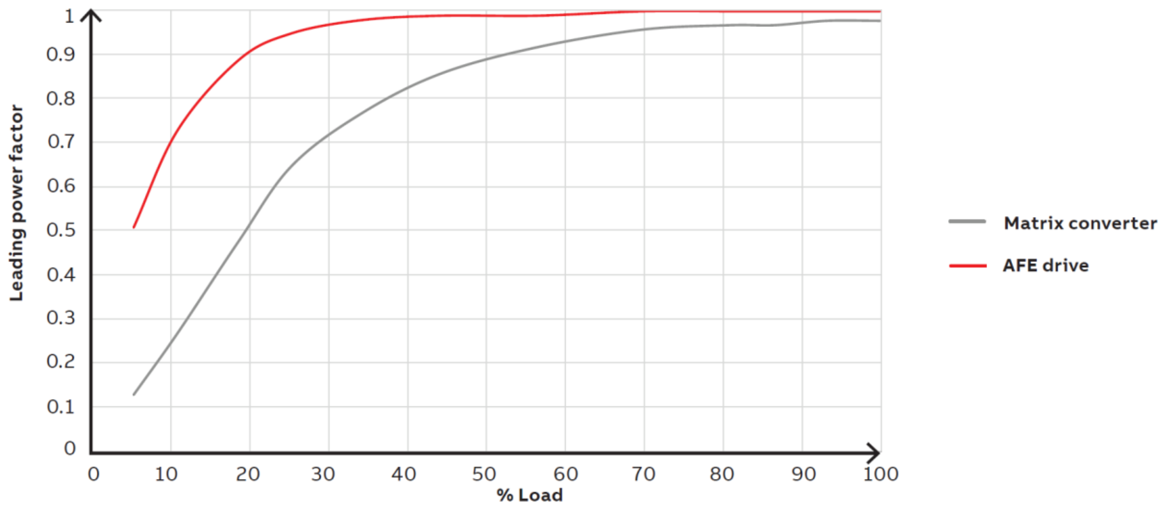

Figure 14. Power factor of an AFE converter (ABB, 2019, s. 8)

The production of reactive power (kVAr) in a ship AC-grid is controlled by adjusting the output voltage of the parallel connected energy sources. In the case of the investigated AC-grid in this thesis, where permanent magnet generators have been chosen, a Genset's production of both active and reactive power are tied together as both are frequency/rpm dependent.

3.9 Cabling

In the investigated AC grid of IT-type, with local protective earthing to the ship's hull, the current carrying conductors are three pieces. For the unipolar DC solution, with local protective earthing, the current carrying conductors are two pieces. The end consumers of the investigated grids are the same for both the AC and DC solutions. 690 VAC is used for electric motors while 400 V and 230 V 50 Hz are used for accommodation equipment. Thereby the comparable difference between the solutions in terms of cabling, is the main grid.

The DC power distribution benefits from lower voltage drop than the AC solution, which is beneficial for long cable runs such as bow thrusters. The DC distribution is affected only by a cable's resistance, while in the AC solution, the voltage drops both due to the cable's resistance and reactance (Hiekka, 2012). The reactance of the AC-grid cables also adds to the reactive power, thus lowering the cos φ of the AC-grid. The voltage drop can be calculated with formulas 3 and 4 below (Sähköinfo Oy, 2017, p. 242).

For a unipolar DC Grid

$$\Delta U = I \cdot 2 \cdot r \cdot s \quad (3)$$

For a 3-phase AC Grid

$$\Delta U = I \cdot s \cdot \sqrt{3} \cdot (r \cdot \cos\varphi \pm x \cdot \sin\varphi) \quad (4)$$

Where:

ΔU is the voltage drop [V],

I is the phase current [A]

s is the length of the conductor [km]

r is the conductor resistance [Ω/km]

x is the conductor reactance [Ω/km]

φ is the angle between the voltage and the current

Factors contributing to the dimensioning of cabling are mainly load-ability, with correction factors caused by environment temperature and cable mounting. Additionally, voltage drop, short circuit durability, short circuit protection and selectivity can increase the dimension of a cable. The dimensioning of a vessel's grid cabling requires detailed consumer lists and cabling route plans. As the electrical grid is wide with many branches, dimensioning and verification of selectivity are normally done with purpose-built software. As the detailed grid design is excluded from this thesis, only a simple comparison between the AC and DC solutions has been made. Solutions for both busway ducting and cabling has been evaluated to highlight the differences.

3.9.1 Example calculation – Busway Ducting / Busway Cabling

The MSB is divided into two halves for both AC and DC solutions, MSB 1 and MSB 2. The grid halves are located in different compartments of the ship. The distance between MSB 1 and MSB 2 is 30 m. Both the AC and DC solutions are dimensioned for 7 MW. This corresponds to following maximum phase currents in the grid halves according to equations 5 and 6.

$$I_{L\,(AC3\sim)} = \frac{P}{(\sqrt{3}\cdot \mathrm{U}\cdot \cos\varphi)} = \frac{7000kW}{(\sqrt{3}\cdot 0{,}750\mathrm{kV}\cdot 0{,}95)} = 5679A\ (3\ wire) \qquad (5)$$

$$I_{L\,(DC)} = \frac{P}{U} = \frac{7000kW}{1{,}07kV} = 6542A\ (2\ wire) \qquad (6)$$

3.9.2 Busway AC-Solution

The bus bars are dimensioned starting from the dimensioning table in Appendix 6. A correction factor of 0,94 has been used to compensate for an ambient temperature of 45°C and a correction factor of 0,984 for 60 Hz frequency according to Appendix 7. The resulting load-ability of the LB 16DC bus bar is 0,94·0,984·6600 A = 6105 A.

3.9.3 Busway DC-Solution

The bus bars are dimensioned from the dimensioning table in Appendix 8. A correction factor of 0,94 has been used to compensate for an ambient temperature of 45 °C. The resulting load-ability for the LB08DC with 12 conductors is 0,94·7094 A = 6668 A.

3.9.4 Bus Cabling AC-Solution

The bus cabling between MSB 1 and MSB 2 is of type LKM-HF 1x150 mm2. For the AC version, the result is a load ability level of 316,2 A per 150 mm^2 cable based on basic load ability of 381 A, with installation in formation of three cables in air at an ambient temperature of 45 °C. A reduction factor of 0,83 has been used for the cable ladder arrangement of three 600 mm ladders on top of each other, with a vertical spacing of 200 mm, where each ladder carries 6 triangular bunches of L1-L2-L3 conductors (ABB, 2000).

Required cabling is 3·18·150 mm^2.

The resulting weight is 3·18·0,03 km·1515 kg/km= 2454 kg for a distance of 30 m.

3.9.5 Bus Cabling DC-Solution

The corresponding DC bus cabling with LKM-HF 1x150 mm^2, results in a load ability of 316,2 A per 150mm^2 cable based on the basic load ability of 381 A in leveled formation in free air with an ambient temperature of 45 °C. A reduction factor of 0,83 has been used for the cable ladder arrangement of two 600 mm ladders on top of each other, with maximum 22 cables per ladder. The ladder spacing is 200mm. (ABB, 2000).

Required cabling is $2 \cdot 21 \cdot 150$ mm^2.

The resulting weight 2·21·0,03 km·1515 kg/km= 1908 kg for the distance of 30m.

3.9.6 Cabling Comparison

The comparison of AC-duct, AC-cable, DC-duct and DC-cable solutions for transferring of 7 MW over a distance of 30 m is presented in table 4 below. The DC solution shows a benefit of reduced material, lower weight, less space and less losses, for both the busway and cable solutions.

Table 4. Comparison of 7 MW cable and busway links between main switch boards

	AC-duct	AC-cable	DC-duct	DC-cable
Cu [mm2/phase]	3840	2700	2880	3150
Weight [kg]	5970	2454	3360	1908
Req. space WxH [mm]	410x210	600x600	150x130	600x300
Losses [kW] with 7 MW Load	26,67	25,48	19,44	19,32
Losses [%] of 7 MW Load	0,38%	0,36%	0,28%	0,28%

The weight column includes only duct and cable weights, duct supports and cable ladders are excluded.

Duct solution losses are datasheet values [W/m] from Appendices 6 and 8. The Cable solution losses are calculated with formula 7 below.

$$P_{tot} = x \cdot I^2 \cdot R_{phase\ total} \cdot L \qquad (7)$$

Where;

P_{tot} = the total cable losses,

x = the number of phases (3 for AC, 2 for DC)

I = the phase current [A]

$R_{phase\ tot}$ = the resulting cable resistance [Ω/km] for the parallel connected cables per phase

L = the cable length [km]

AC-cable solution: Resistance for 18 pcs of parallel connected 150mm2 LKM-HF cables have a resistance of 0,00877778 Ω/km at 90 °C.

DC-cable solution: Resistance for 21 pcs of parallel connected 150mm2 LKM-HF cables have a resistance of 0,00752381 Ω/km at 90 °C.

3.10 High Voltage Shore Connection

The shore connection follows the same modular concept. The transformer and possible converter are housed, depending on the required power level, in a 20ft or 40ft standard container. By changing to a suitable shore connection module, both container vessel standard 6,6 kV and cruise ship standard 11 kV can be used. Connection can be done either to 50 Hz or 60 Hz grids.

The variable frequency AC grid can be synchronized to a 50 Hz grid without a shore connection converter with all energy sources. This synchronization process is described in section 4.2.2 *Example 3*. Synchronization to a 60 Hz grid is also possible without a shore connection converter, if the transfer is done via the battery or PEMFC converters instead of Gensets.

4 Control Systems

With the comparable grid design elements investigated in chapter 3, and summarized in chapter 6 and 7, the study moves on to the control system design. The requirements of control system are quite similar for both the DC grid and the variable frequency AC grid solutions. The key element for the control system is modularity and replaceability.

A vessel is typically built with an Integrated Automation System (IAS) for controlling of the vessel's functions and gathering of information and alarms from various sub systems, such as propulsion control systems and energy source control systems. The IAS is the Human Machine Interface (HMI) of a vessel´s technical systems. The navigational part has traditionally been a separate IAS, gathering information from various navigational systems. On modern vessels, these IAS's can be combined or linked together.

An IAS can be divided into several parts, both physically and program vise, to add redundancy and to get a clearer view of the control system. As the possibility to replace the energy module types is introduced, a further level of adaption is required by the IAS. The proposed control system topology for the modular energy module concept consists of an overlaying Control, Alarm and Monitoring system, an Energy Management System (EMS) and a Power Management System (PMS). The functions of the systems are presented in chapters 4.1, 4.2 and 4.3. The basic topology is presented by figure 15 below. The black lines show the primary signal path, and the red dashed line shows the occasional signal path.

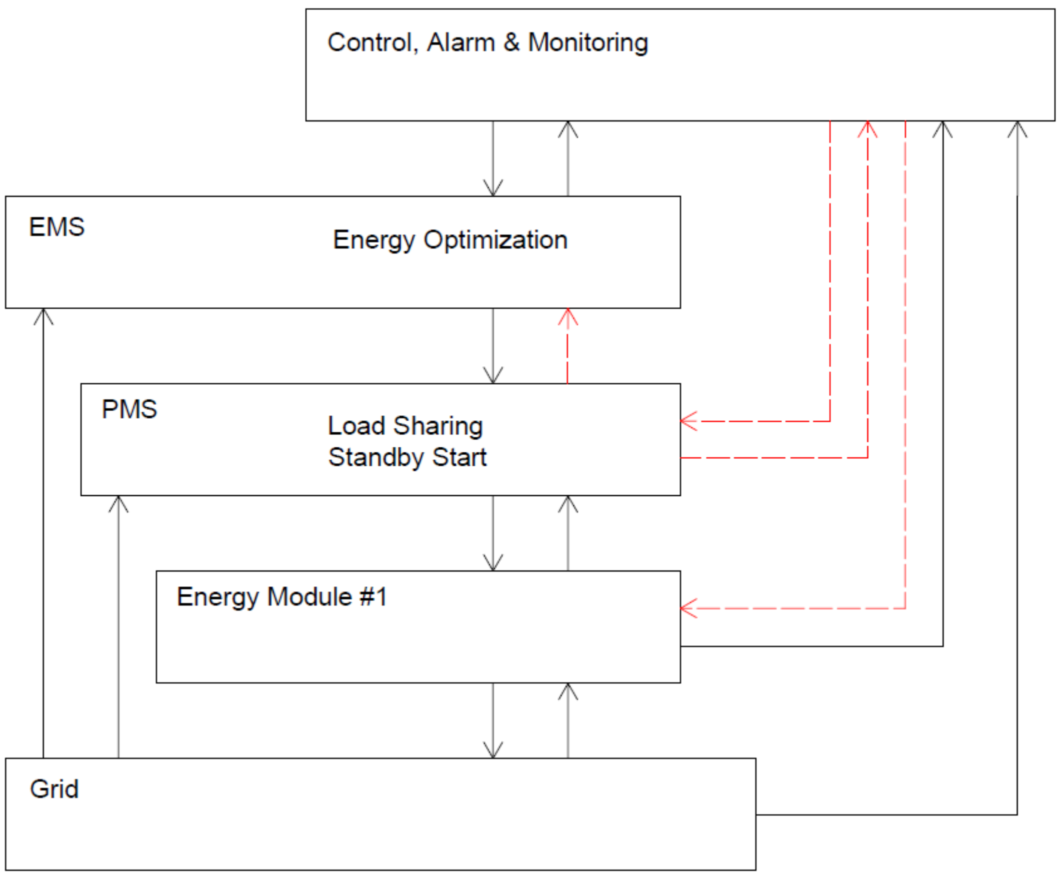

Figure 15. IAS basic topology diagram

A block diagram of the IAS system can be seen in figure 16 below. The back bone of the control system is the IAS1.1 and IAS1.2 Programmable Logic Controller´s (PLC´s), and their redundant PLC´s IAS2.1 and IAS2.2. The energy modules, marked EM_n, such as Gensets, PEMFC and Batteries have internal control systems supervising the energy conversion process. These systems are interfaced to the IAS via an optical Industrial Ethernet connection, enabling high speed communication with mitigated disturbance from common mode currents. The back-up system is fully redundant, including separate cabling.

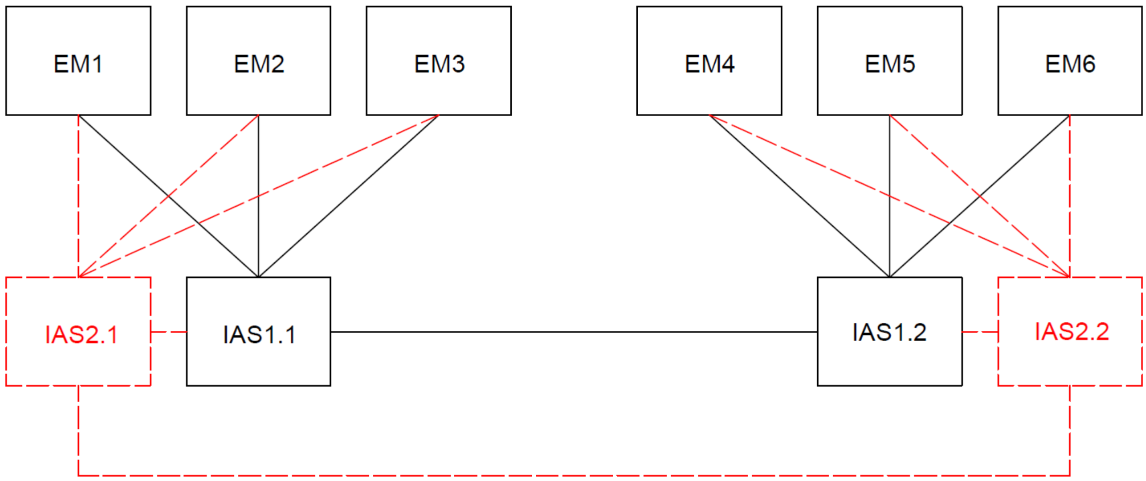

Figure 16. IAS basic block diagram

When a module is replaced, a handshaking with the IAS is made to establish following parameters:

- Type of energy source (voltage/load characteristic)
- Allowed voltage window
- Nominal current
- Overload limit (order to offload the module)
- Critical failure (offload and disconnect the unit immediately)
- Droop setting

4.1 Energy Management System

The purpose of an Energy Management System (EMS) is to maximize vessel energy efficiency and minimize emissions by balancing the load between parallel connected energy sources optimally. Typical task intervals for the EMS is from seconds to minutes depending on the task. Possible system learning and optimization process, for example by utilizing Artificial Intelligence (AI), based on known energy module settings in combination with measured emissions, can be a part of the EMS. The operating crew has the possibility to set limitations and prioritize the use of certain energy modules depending on the existing circumstances such as traffic area, energy source maintenance etc. American Bureau of Shipping lists the following minimum requirements for the investigated vessel's Energy Management System (ABS, 2020, p. 26).

● Control and monitoring of Energy Storage System (ESS) to ensure sufficient availability of spinning reserve.

● Monitoring of Fuel Cell Power System to verify correct function and thereby availability as primary energy source.

● Supervision of load sharing between primary energy sources and ESS.

● Maintain the energy supply to the essential and non-essential loads.

● A failure within the EMS management system is to be alarmed at a manned control station.

The optimal parametrization of the EMS, is dependent of the used energy sources and the current load level. For example, figure 17 below shows the characteristic efficiency-load relation for the Genset (comparable with "HSDI Diesel") and PEMFC (comparable with "Fuel Cell Systems with Hydrogen") (van Biert, Mrozewski, & ´t Hart, 2021).

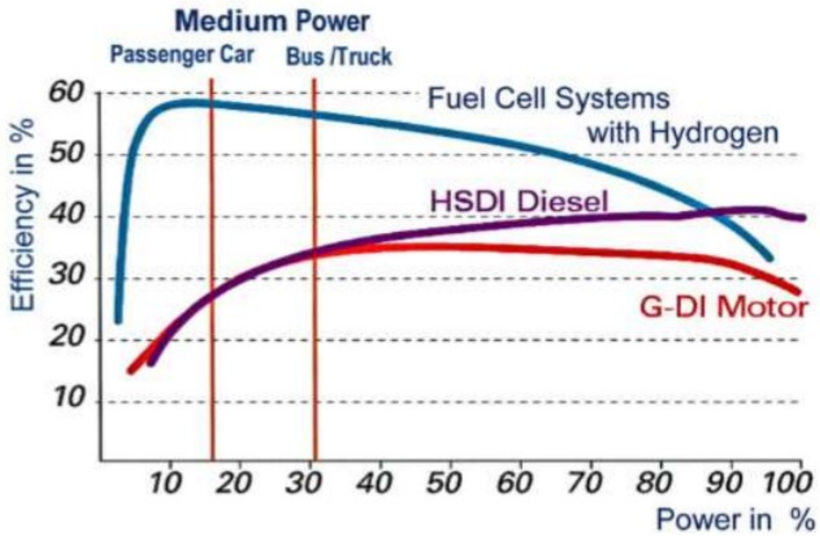

Figure 17. Characteristic efficiency vs. load relation for Genset and PEMFC

4.2 Power Management System

The purpose of the Power Management System (PMS) is to synchronize the energy modules and perform load sharing between connected units according to setpoints created within the EMS. Typical task interval for a PMS system is from grid cycle (20ms for a 50Hz grid) to minutes, depending on the task.

Tasks requiring a quicker response (micro seconds up to grid cycles), such as peak shaving and disconnection of DC-bustie breakers, are controlled directly by the converter module of the ESS and the converter module of the DC-bustie breaker.

4.2.1 Failure behavior

In case of a critical failure of in one of the connected energy sources, the PMS system starts up a standby-unit and disconnects the faulty unit. The ESS supports the grid during the switch over if needed.

In case of a Black-Out the PMS splits the grid into two isolated parts, isolates the fault location (if sensed by the system prior to the Black-Out), starts up all available energy sources, the quickest connects immediately to the cold grid and the following are synchronized one by one. If the short circuit location is unknown, all inverter-controlled loads are disconnected before the energy sources are reconnected, where after the loads are reconnected one by one starting from essential loads. A Black-Out situation on a hybrid ship can be caused by a critical failure of a primary energy source combined with an insufficient spinning reserve. It is thereby important that the batteries are leveled regularly to ensure the State Of Charge (SOC) measuring being accurate. For the AC solution a black-out can also be caused by a busbar short circuit if the grid halves are connected. For the DC-solution, a busbar short circuit situation causes a half black-out as the DC-bustie breaker splits the grid before a complete black-out occurs.

In case of an internal failure of the power management system, the available electrical power is to remain unchanged. The failure is to be alarmed at a manned control station (ABS, 2020, p. 26). In this situation load sharing is possible only manually, until the cause of failure has been corrected.

4.2.2 Load sharing behavior

The load sharing behavior is dependent of the used energy sources. For the investigated main energy sources, the Genset and the PEMFC, the PEMFC is more sensitive to loadvariations than the Genset. Quick load variations causes cell degradation and shorter lifetime for the PEMFC (van Biert, Mrozewski, & ´t Hart, 2021). The recommended ramp for a PEMFC is 1% of full power per second (Bogen & Jensen, 2020). For the single FCWave 200 kW unit this corresponds to 2 kW/s, and for the whole energy module of 15 units, 30 kW/s.

The Genset can handle quicker load changes and instant load steps, but with the drawback of decreased SFOC. Both investigated main energy sources benefit from the peak shaving supplied from the battery. A comparison of load response and startup times for the investigated energy sources; Genset, PEMFC and NMC Battery, are presented in table 5 below.

Table 5. Energy module load response and startup times

	Load increase	Start Up and Conn. Time
Genset	Max. instant load step 33% Recommended 3,33% /s	~10 s DC ~ 45 s AC
PEMFC	1% per second	~3 s
Battery	instantaneous	instantaneous

For parallel connected units in the DC grid, the output power of an energy module is raised by giving a higher voltage setpoint, and respectively lowered by giving a lower voltage setpoint. For the AC solution, the output power of a parallel connected energy module is raised by raising the frequency setpoint, and respectively lowered by giving a lower setpoint.

In general, the primary transient loads are covered by the batteries. The secondary means for transient load sharing is proposed to be done with droop for both the AC and DC solutions. If only one type of main energy source is used, for example Gensets, are all connected energy modules given the same setpoint and the same droop, for ex. 1% for the DC-solution where all energy sources are connected via converters. As the droop is equal in %, the connected energy sources will be loaded equally in % during transient load changes, regardless of the energy source power level. If a combination of different main energy sources is used, the response to transient load changes can be adjusted suitable for the energy sources by adjusting the droop. After the load transient, the PMS balances the loads by correcting the setpoints for the energy modules.

The AC-solution with directly connected generators is proposed to have a slightly bigger droop of 4-5%, which is a commonly used value for parallel connected Gensets. In the AC-solution the direct connected Gensets, with variable frequency and voltage, will generate the voltage and frequency setpoints for other parallel connected energy sources.

Example 1. Gensets as main energy source + Battery for peak shaving, spinning reserve and emission minimization in ports.

The output voltage of the Permanent Magnet Genset in different load conditions is presented in the figure 18 below.

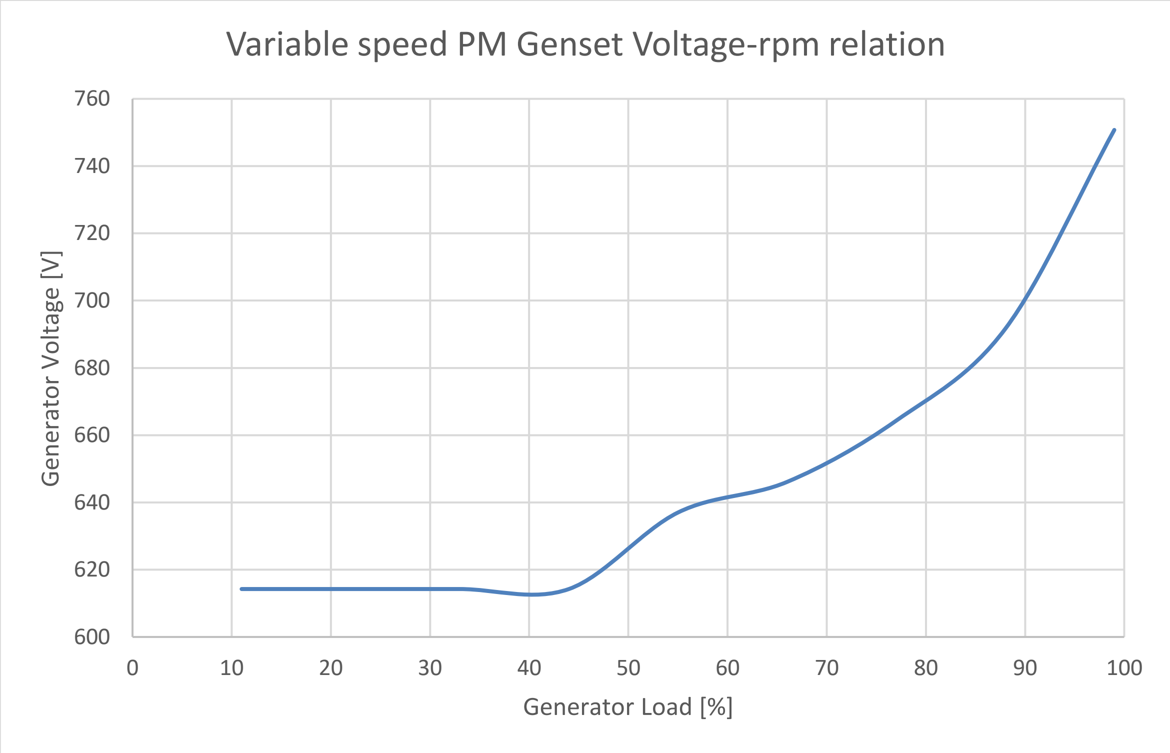

Figure 18. PM Genset voltage rpm dependency

As there is no converter between the PM Genset and the grid in the AC solution, the busbar voltage varies between 615…750 VAC depending on the Genset rpm. The output voltage is thereby load dependent. As the ESS works as a peak shaver and a spinning reserve, the ESS converter setpoint must be varied depending of generator load and number of connected generators.

Example 2. FC as main energy source + Battery for peak shaving and spinning reserve.

The output voltage of a FC is the opposite to the variable speed PM Genset. The FC voltage is highest at low loads and the voltage drops as the load increases. The characteristic is presented in figure 19 below. As the FC modules are converter controlled in both AC and DC grids, the output voltage can be kept at the desired level, Genset-load-dependent in AC solution, and ~1070 V in the DC solution. The DC voltage is fine adjusted depending on the load sharing situation.

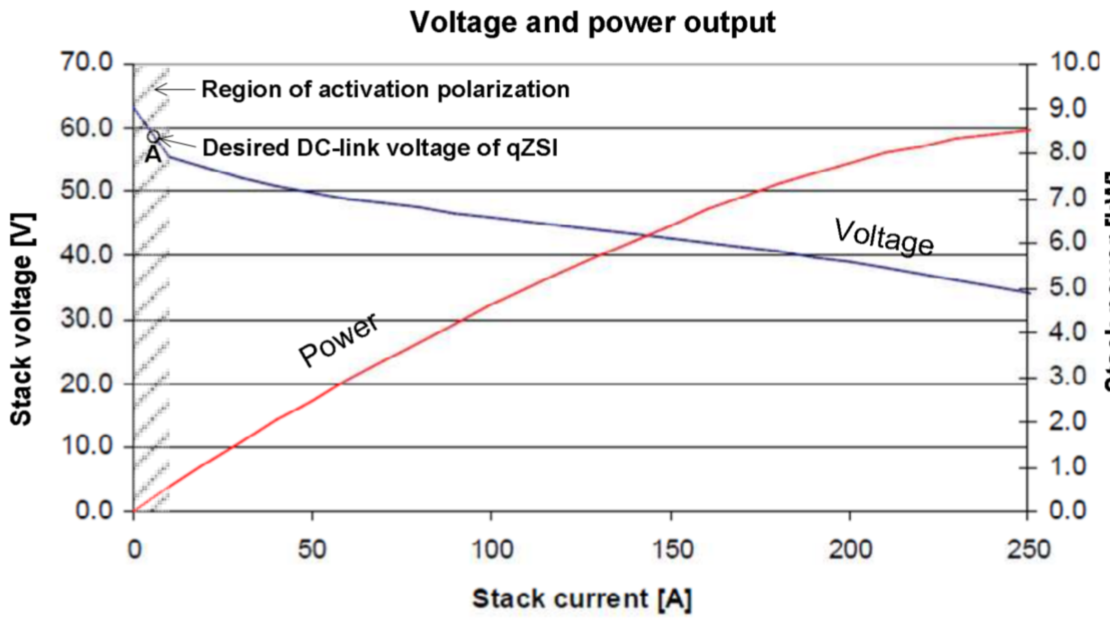

Figure 19. Characteristic dropping voltage at increased load for a PEMFC (Zakis, Vinnikov, Roasto, & Strzelecki, 2010)

Example 3. Shore connection

Whilst on shore connection, the power of 2 MW is calculated to carry both the cargo operations and charging of the onboard batteries.

The AC solution is done without a shore connection converter. When synchronizing with Gensets, the PMS switches to steady 50 Hz control mode before synchronizing to shore grid. As the DG´s are equipped with PM generators, with an output voltage of 0,455 V/rpm, the generator voltage will be 682,5 V @ 1500 rpm (50 Hz), which is within the -10…+6% tolerances of standard 690 V voltage level. The load-ability of the Genset at 1500 rpm is 80%. As the ship side voltage is slightly lower than the shore side voltage, the reactive power [kVAr] will travel controlled from shore to ship during the time of parallel running and load transfer from ship's Gensets to the shore connection. The active load [kW] is transferred to the Genset by increasing the Genset fuel supply, respectively decreased by reducing the fuel supply.

The vessel can also synchronize to 60 Hz grids without a separate shore connection converter if the synchronization is done either via PEMFC or Battery converters.

4.3 Control, Monitoring, Alarm and Safety Systems

The purpose of the Control, Monitoring and Alarm parts of the IAS is the user interface for the operating crew, whether the crew being located onboard or in a Remote Operation Center (ROC). The Safety System functions, such as automatic shutdowns and standby starts are automatic functions which do not require any action from the crew. The crew is informed via triggered alarms. Automatic safety functions and alarm system sensors are to be individual.

The concept with replaceable modules requires flexibility of the IAS. A handshaking is required at module change to establish the required control and alarm parameters. The minimum required alarm points and shutdowns states of marine hybrid systems are presented in Appendix 9 (ABS, 2020).

4.4 Energy source specific protection devices

The health of each energy source is monitored by the manufacturer specific control system built within the energy module. These monitoring systems communicates with the ship's IAS. The energy sources specific protection devices are listed in tables 6, 7 and 8 below.

In addition to these tables, each energy module is equipped with fire detection and energy source specific fire distinguishing systems. For flammable gas solutions, the modules are equipped with a type specific gas detection and gas disconnection system as presented in Appendix 10.

Table 6. Genset specific protection devices

Type	Setting	Delay	Automatic Shutdown
Over Voltage	800 V	10 s	X
Under Voltage	525 V	10 s	X
Reverse Power	-8%	10 s	X
Non Essential Trip	1,0xIn	8 s	-
Overload	1,1xIn	20 s	X
Short Circuit	2,5xIn	450 ms	X
Overspeed Electric	1740 rpm	-	X
Overspeed Mech.	1760 rpm	-	X
Converter Failure DC	-	-	X
Lubrication Oil Fail	Double sensors	-	X

Table 7. PEMFC module specific protection devices

Type	Setting	Delay	Automatic Shutdown
Stack Over Voltage	$1{,}1xU_{max}$	5 s	X
Stack Under Voltage	$0{,}9xU_{min}$	5 s	X
Overload Stack	$1{,}1xP_{max}$	5 s	X
Overload Converter	1,5xPmax	5 s	X
Converter Failure	-	-	X
Stack Temp Monitoring	N/A	N/A	-
Insulation Monitoring	N/A	N/A	-
Brake Resistors for Total Discharge	-	-	-
Gas Detection and Gas Disconnection	See Appendix 10	-	X

The minimum protection devices required by ABS for an ESS are listed in Table 8 below.

Table 8. Minimum monitored parameters and automatic shutdowns for an ESS (ABS, 2020, p. 27)

Systems	*Monitored Parameters*		*A & D*	*Auto Shut down (1)*	*Notes [A = Alarm; D = Display; x = applies]*
Energy Storage System(3)(4)	A1	State of Charge (SOC) – low	x		
	A2	Charging/Discharging - failure	x	x	
	A3	Current – high	x	x	
	A4	Overload	x	x	
	A5	Voltage – high and low	x	x	
	A6	Frequency – high and low (only AC systems) (5)	x	x	
	A7	Cooling or fan - failure	x	x	
	A8	Emergency Stop (2)	x	x	See 5/1.7.iv)
	B1	Cooling medium pressure – low or, temperature – high	x		For subsystem having a cooling system.
	B2	Ventilation - failure	x	x	For subsystem having a ventilation system
	B3	Transformer - failure	x	x	For subsystem having a transformer
	B4	Converter - failure	x	x	For subsystem having a converter
	B5	ESS room or space – high ambient temperature	x		
	B6	ESS (cell, module) – high temperature	x	x	Alternative arrangements can be accepted on risk assessment basis

5 Results

The investigated energy module size and weight information, including limitations, is presented in section 5.1. The investigated modularized energy sources are presented in sections 5.1.1-3. Section 5.2 briefly presents the maintenance aspect of the modularized concept. And section 5.3 presents energy source specific efficiency comparisons to evaluate grid efficiency.

5.1 Energy module types

The investigated energy module types of this thesis are listed below. The modular energy concept is not limited to these types, module power levels or module sizes. The technical development of the energy sources will lead to increased power density of the energy modules, thus should these values be seen as working numbers rather than final values for this concept.

- 2300 kW Genset module
- 3000 kW Fuel cell module
- 4000 kWh Battery module with maximum output of 4000 kW (DC-solution), 3000 kW (AC-solution)

Figure 20 below presents different container size outer dimensions.

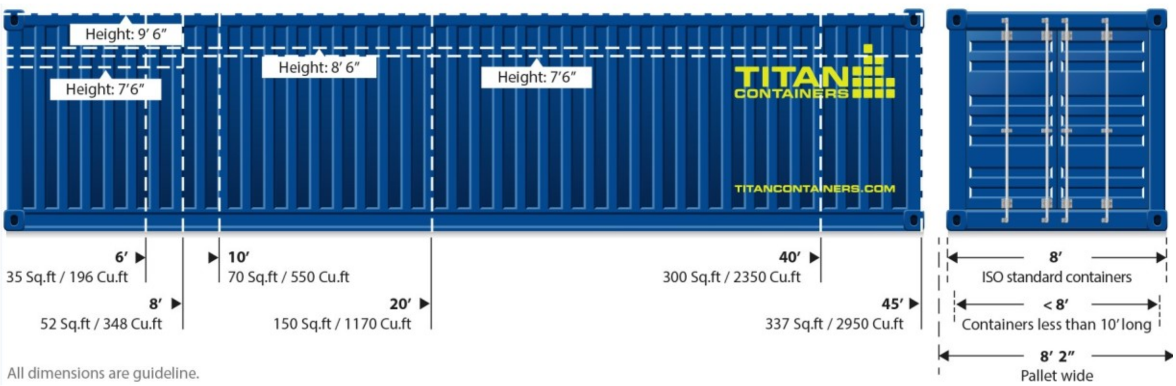

Figure 20. Shipping container external dimensions (Titancontainers.co.uk, 2021)

The external and internal dimensions of the 40 ft high cube container are presented in table 9 below. The internal dimensions have some variation depending on the container manufacturer.

Table 9. Metric dimensions of shipping container

	Length [m]	Width [m]	Height [m]
External	12,18	2,44	2,90
Internal	12,11	2,34	2,69

The tar weight of the 40 ft high cube container is ~4,25 metric tons and the payload for a standard container is 26-28 metric tons. Container solutions requiring higher payload, such as Battery containers, are custom built (Hapag-Lloyd, 2017). Heavier than standard containers have restrictions in road transports. Of the energy modules investigated in this thesis, the battery module exceeds the road transport limit clearly, and the Genset module is near the maximum weight of unrestricted road transport. If unrestricted road transport is required, the heavy modules can be divided into 2 pcs of 20 ft high cube containers. The payload for a 20 ft container is slightly larger than for a 40 ft container due to smaller tar weight.

The Safe Working Load (SWL) limitation of a container crane is dependent of type and manufacturer, but most modern cranes have a capacity of at least 65 metric tons. Therefore 65 metric tons have been used as the maximum weight for the energy modules in this thesis.

The energy modules have been chosen to be water cooled to maximize the power density of the modules and to be able to collect waste heat for the ship's needs. Water cooling also minimizes the contact with harsh ambient conditions, thus improving resistance against corrosion and contamination.

The transformers needed to connect the fuel cells and battery modules to the variable frequency AC grid are located outside of the energy modules due to space limitations. The footprint and weight of these transformers decrease the variable frequency AC grid power to size ratio significantly. Without these extra transformers, the remaining converters for the AC and DC grids are approximately of equal size and weight, when looking at the whole grid of the investigated example ship. In the DC solution, as the link between the main busbars is dimensioned to 7 MW, the dimension of the semiconductor bustie breakers is significant, approximately 30% both in terms of volume as well as weight of all required converters.

A modular energy source concept has a number of requirements for the energy modules. The energy module needs to have a standardized footprint regarding external connections. As a minimum, the connections listed below are needed. This list might need to be extended if other fuel types are implemented.

- Fuel inlet (liquid)
- Fuel outlet for circulation (liquid)
- Fuel inlet (gas)
- Air inlet
- Exhaust
- Cooling water inlet and outlet for energy source
- Cooling water inlet and outlet for converters
- Control system connection
- Electrical power output

Managing to locate the connectors to the same positions for different energy module types is challenging and inevitably lead to compromises. Compromises can be minimized on a vessel design where certain energy modules have their dedicated slots on the vessel.

Another essential requirement for the different energy modules is fire detection and fire suppression. Each energy module is to have an integrated fire extinguishing system purpose built for the energy or fuel used in each container type.

A control system with standardized protocol for connecting to the vessel's IAS is also needed.

5.1.1 Genset module

The Genset module presented in this thesis consists of two standard Wärtsilä 16V14 (W16V14) ICEs driving two ABB PM generators and two converters housed in a standard 40 ft high cube container. The maximum continuous power output of the module is 2310 kW. The gensets use LFO as fuel in this thesis, but the modules are naturally not constrained to any specific fuel type by the modular concept. As there at writing moment are no ready containerized solutions for the twin-W16V14 solution, a figure presenting a containerized solution of a W6L20 is presented below to give an understanding of the Genset module (Wärtsilä, 2014). The W6L20 Genset has a continuous electrical output of 1255kW @ 1200 rpm (60 Hz).

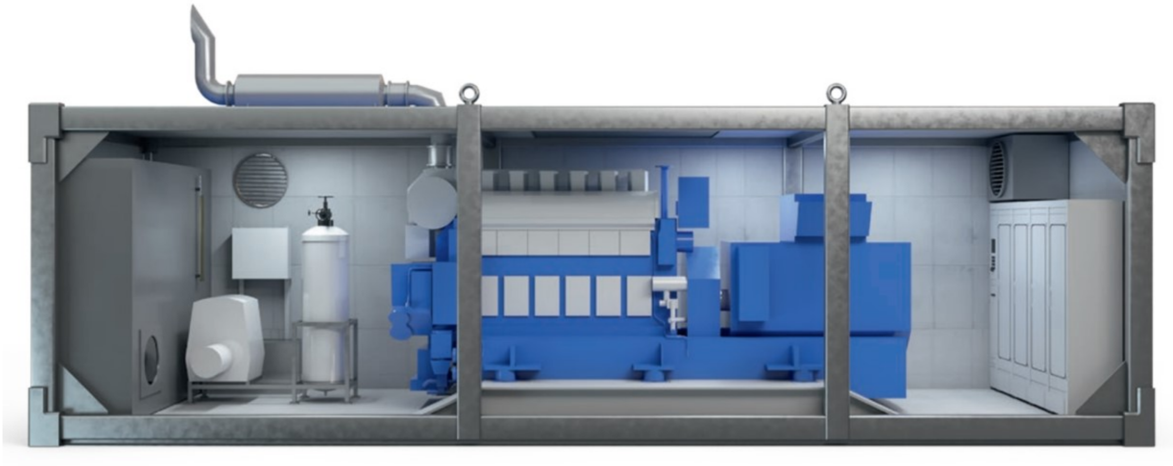

Figure 21. Wärtsilä Containerized Genset Solution (Wärtsilä, 2014)

The Genset main technical data is presented in Appendix 1. The electrical diagrams for AC and DC Genset solutions are presented in Appendix 11 and 12.

5.1.2 Fuel Cell module

The Fuel Cell module consists of a 40 ft standard high cube container housing 15 pcs of á 200 kW Ballard FCwave^{TM} PEMFC units with individual converters. Ballard FCwave^{TM} PEMFC was chosen for this thesis since as fueled by pure hydrogen the emissions from the FCwave^{TM} is pure water, the unit is scalable, modular and a standard product. Ballard also aim to have the FCwave^{TM} type approved for the marine market during 2021. As the main focus of this thesis is to evaluate the ship's electrical grid for modular energy concept, a on the market product gives a useful perspective.

The figure 22 below shows three parallel connected FCwave^{TM} modules á 200 kW. The piping to the units is intended to be mounted under a false floor, thus protecting the pipes and enable serviceability. The connections of the unit are as follow:

1. Hydrogen inlet (double wall design)
2. Cabinet ventilation inlet
3. Electrical power and control connectors
4. Low temperature cooling water inlet DN32 (to electrical converters)
5. Low temperature cooling water outlet DN32 (from electrical converters)
6. Process water outlet
7. High temperature cooling water inlet DN50
8. High temperature cooling water outlet DN50
9. Ambient air intake
10. Ambient air intake
11. Process outlet (to be vented outside of vessel)
12. Enclosure ventilation (to be vented outside of vessel)

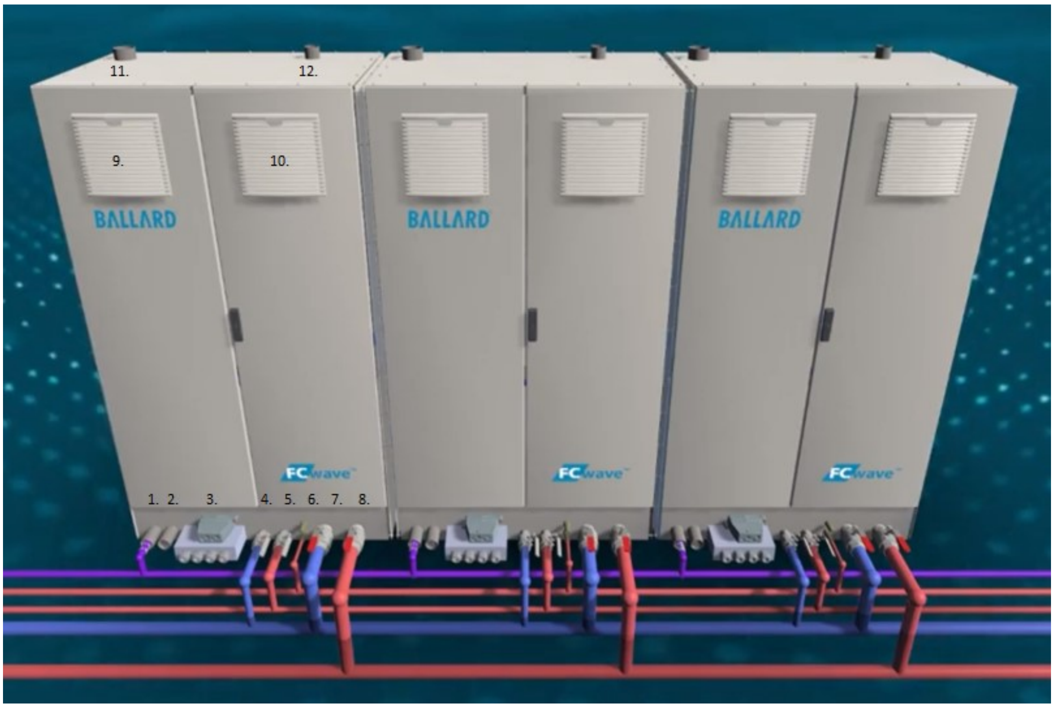

Figure 22. Parallel Connection of Ballard FCwave™ 200 kW PEMFC Modules (HySeas III, 2021)

The Fuel Cell main data is presented in Appendix 2. And the electrical one-line diagrams for AC and DC PEMFC solutions are presented in Appendices 13 and 14.

5.1.3 Battery module

The battery module used in this thesis is based on an existing solution from *Shift 2 Clean Energy* (SHIFT), where a 5456 kWh NMC battery, including converters are housed in a 40 ft high cube container. The SHIFT container has an extra roof mounted space, thus making it a non-standard shape. Also, the weight of the SHIFT container is 80 metric tons, which exceeds the weight limit of maximum 65 metric tons used in this thesis. Therefore, a working value of 4000 kWh has been chosen for a standard 40ft high cube container, including converters. The SHIFT 40 ft High Cube Container specifications are presented in Appendix 3.

The battery is over sized for the need of peak shaving and spinning reserve that are presented as in this thesis. But the writer anticipates to compare the suitability of the grid also for an all-electric costal vessel utilizing the modular energy concept. A solution, where pre-charged energy modules could be lifted onboard the vessel instead of charging during harbor visits, a solution for a remote port with weak electrical grid, unsuitable for high capacity charging during port calls.

Per definition, at a discharge rate of 1 C, a battery rated 4000 kWh should be able to supply 4000 kW for one hour. As the battery module in the thesis has a comparably high capacity, the discharge rate can be restrained. The reference battery unit allow discharge rates at 1 C continuous and 2 C peak. The charge rate is 1 C. The same rates have been used for battery module in this thesis. The main data for the battery modules is presented in table 10 below.

Table 10. Battery module main values

	AC module	DC module
Capacity [kWh]	4000	4000
Max. Power output [kW]	3000	4000
C-rate	0,75	1

The AC module output has been chosen lower as an increase from 3000 kW to 4000 kW would double the required space for the converter module, from chassis size 1x CH64 to 2x

CH64. Figure 23 below gives an understanding of the battery module investigated in this thesis.

Figure 23. Direction giving 20 ft battery module (Shift 2 Clean Energy, 2021)

5.2 Maintenance

Major preventive maintenance of the energy modules is intended to be done with the module lifted or rolled of the ship. The preventive maintenance can be either condition based or periodical according to OEM instructions. Smaller maintenance and inspection work can be carried out onboard the ship.

The fuel cell stack is typically changed after an output voltage degradation of 20% (Alfredsson & Swenson, 2017). The lifetime expectancy for the FCwave is over 30 000h (Ballard Power Systems, 2020). Maintenance interval of W16V14 is 20 000h (Wärtsilä, 2019). Battery module maintenance interval is depending of the use. SHIFT states a service life of 13 000 cycles @ 80% Depth of Discharge (DoD) for the NMC cell. A direction giving cell replacement period for marine battery systems is 10 years.

Compared to a traditional fixed frequency AC grid, both the variable frequency AC and DC grids introduce additional components in form of converters, components that require maintenance. The design life of power electronics is typically in the range of 15-20 years, thus likely requiring a midlife upgrade or overhaul of the converter units during the vessel’s operational life. The components with shortest lifespan are capacitors and cooling fans (Hiekka, 2012).

On the other hand, (Habermaas & Thurner, 2020, p. 1) claim that by the lowering the engine speed, maintenance intervals can be extended by 20%, thus giving variable frequency AC and DC grids an advantage when comparing the Life Cycle Costs of the system designs with a fixed speed AC grid

5.3 Grid efficiency

The ship grid efficiency comparison has been done with following setup. The example vessel M/S Module has had a fixed accommodation and reefer socket load of 300 + 300 kW, and a fixed auxiliary load (MCC-load) of 100 + 100 kW. The propulsion motors have been loaded at steps of 1 + 1 MW. The calculations have been done for ½-ship, and the results have been doubled at the last rows to present the whole ship situation.

The ICE load profile has been provided by Wärtsilä (Personal communication with General Manager, System & Product Performance 15.3.2021). The generator efficiency values originate from data received from ABB (Personal communication with Global Product Manager, Generators 22.6.2021). Converter and filter efficiency values are supplied by Danfoss (Personal communication with Product Manager, Premium Drives 20.4.2021). Transformer efficiency values are estimated from datasheets of similar sized transformers. The propulsion motor losses are approximated by the writer as no real values were available at the time. This approximation has however no impact for the grid comparison, as identical values have been used for both grid solutions. Cabling losses are estimated with the example calculation presented in chapter 3.9.

The results for the different energy sources are presented in the following chapters 5.4.1, 5.4.2 and 5.4.3.

5.3.1 Genset Solution

Figure 24 below presents the difference in SFOC for a Genset, for a fixed frequency AC-grid, a variable frequency AC-grid and a DC-grid. The figure shows that with the 45…55 Hz frequency range, the optimal Genset speed setpoint can be used down to 30% load. The variable speed DC benefits of a 0,83% advantage in SFOC at 20% load compared with the variable speed AC solution, and an 8,7% advantage at 10% load. Generally, a Genset load is seldom designed to be under 30%. For a hybrid Genset solution with peak shaving battery and spinning reserve, the optimal load level around 70-90 % can be kept for connected Gensets.

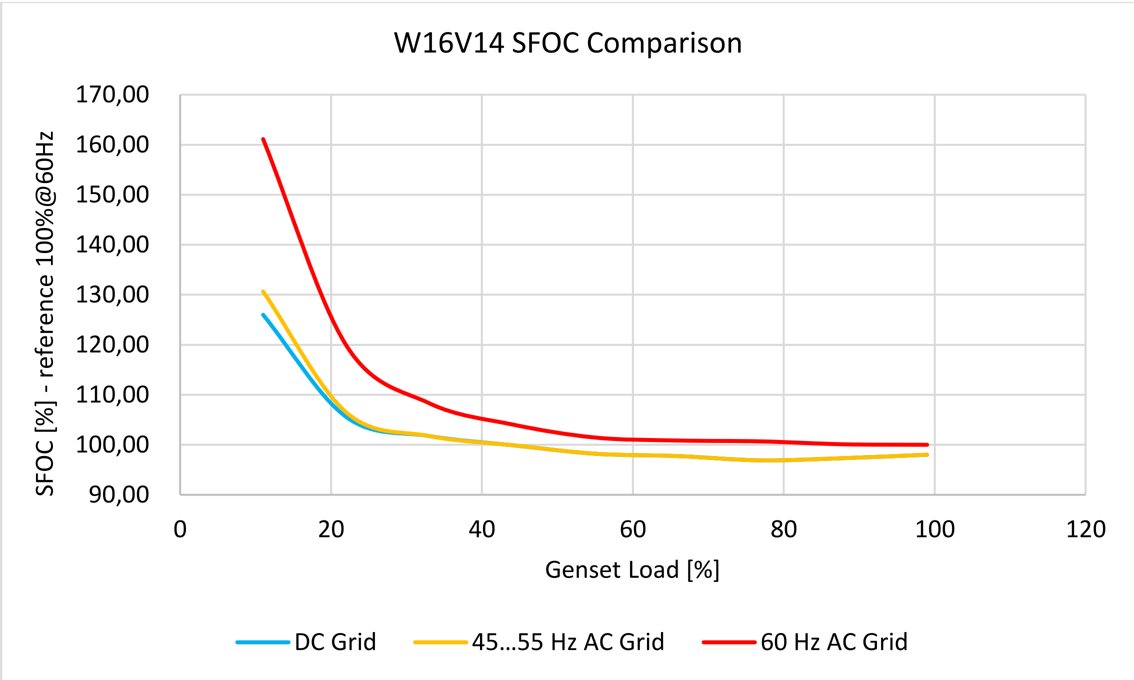

Figure 24. W16V14 SFOC with different grid types

Figure 25 below presents an efficiency comparison between synchronous generator (SM) and Permanent Magnet (PM) generator based on values received from ABB (Personal communication with Global Product Manager, Generators 22.6.2021). The same figure presents also the comparison of a fixed speed 60 Hz solution with a 45…55 Hz variable speed solution.

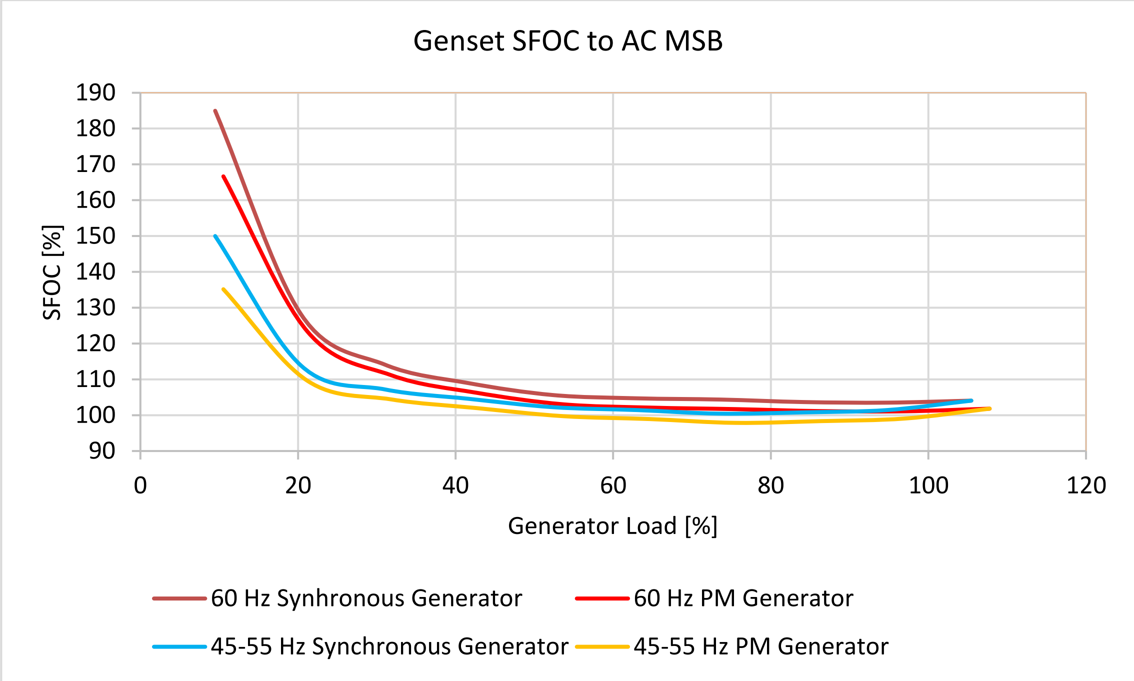

Figure 25. PM and SM generator comparison with fixed and variable speed solutions

To evaluate the grids, the same PM generator has been chosen for both the AC and DC grid solutions. With the variable speed AC grid investigated in this thesis, the Genset can use the same optimal rpm as the DC grid down to 30 % load, which corresponds to the Danfoss converter minimum input frequency of 45 Hz according to data sheet. According to Danfoss (Personal communication with Product Manager, Premium Drives 30.3.2021) even lower frequencies are accepted, which would benefit the variable frequency AC solution also for loads under 30 %.

The grid efficiency of the variable frequency AC and DC Genset solutions are compared in table 11, and presented in figure 26 below. The efficiency difference with the chosen products from Danfoss, presents a benefit of 0,44…0,70 % advantage for the DC grid solution when the propulsion motors are used, but a disadvantage of 0,29 % with purely accommodation and reefer load. The main benefit for the DC grid comes from the reduced filter losses, as the required dU/dt filter for the Generator in the DC solution has significantly lower losses than the required LCL filter for the propulsion motor AFE rectifier in the AC solution. As the Propulsion Motors (PM) are the dominant consumer of the grid, the high filter losses caused by rectifying at the PM converter are clearly visible in the results.

At Genset module loads above 95%, the excess energy is fed from the batteries. At this load level, the DC grid solution benefits from a more efficient conversion and the excess losses caused by the transformer used in the AC grid.

Table 11. Genset solution - grid efficiency calculation

DC Grid Efficiency - 1/2 of a 5+5MW ship grid - 4x1150kW Genset with PM Generator + Battery						
Connected DG´s [pcs]	1	4	4	4	4	4
Load Hotel [kW]	300	300	300	300	300	300
Load MCC [kW]	100	100	100	100	100	100
Load Main Thruster [kW]	0	1000	2000	3000	4000	5000
Total Load [kW]	400	1400	2400	3400	4400	5400
Load / Gen [kW]	400	350	600	850	1100	1150
Load / Gen [%]	34,78	30,43	52,17	73,91	95,65	100,00
Load Battery [kW]						800
Losses / Generator [kW]	12,8	11,2	13,2	14,195	19,25	20,125
Losses AC/DC / Generator [kW]	4,06	3,71	5,47	7,46	9,44	9,81
Total losses conn. Generators [kW]		59,64	74,68	86,62	114,76	119,74
Losses Battery Converter [kW]						10,4
Losses PM Converter [kW]		29,85	35,4	33	44	56
Losses Propulsion Motor [kW]		50	80	90	120	150
Drivetrain efficiency [%]		90,94	92,66	94,19	94,04	94,31
Losses Hotel Inverter [kW]	9,19	9,19	9,19	9,19	9,19	9,19
Losses Hotel Transformer [kW]	3	3	3	3	3	3
Losses MCC Inverters [kW]	3	3	3	3	3	3
Total Losses 1/2-ship [kW]	32,05	154,68	205,27	224,81	293,95	351,33
Whole ship grid losses [kW]	64,1	309,36	410,54	449,62	587,9	702,66
Overall ship grid efficiency [%]	**92,58**	**90,05**	**92,12**	**93,80**	**93,74**	**93,89**

AC 45-55Hz Grid Efficiency - 1/2 of a 5+5MW ship grid - 4x1150kW Genset with PM Gen. + Battery						
Connected DG´s [pcs]	1	4	4	4	4	4
Load Hotel [kW]	300	300	300	300	300	300
Load MCC [kW]	100	100	100	100	100	100
Load Main Thruster [kW]	0	1000	2000	3000	4000	5000
Total Load [kW]	400	1400	2400	3400	4400	5400
Load / Gen [kW]	400	350	600	850	1100	1150
Load / Gen [%]	34,78	30,43	52,17	73,91	95,65	100,00
Load Battery [kW]						800
Losses / Generator [kW]	12,8	11,2	13,2	14,195	19,25	20,125
Total losses conn. Generators [kW]		44,8	52,8	56,78	77	80,5
Losses Battery Converter [kW]						14,96
Losses Battery transformer [kW]						6
Losses PM rectifier [kW]		23,88	34,12	45,13	56,95	69,39
Losses PM inverter [kW]		29,85	35,4	33	44	56
Losses Propulsion Motor [kW]		50	80	90	120	150
Drivetrain efficiency [%]		90,41	92,23	93,80	93,66	93,48
Losses Hotel Rectifier [kW]	5,1	5,1	5,1	5,1	5,1	5,1
Losses Hotel Inverter [kW]	6,09	6,09	6,09	6,09	6,09	6,09
Losses Hotel Transformer [kW]	3	3	3	3	3	3
Losses MCC Converters [kW]	3,73	3,73	3,73	3,73	3,73	3,73
Total Losses 1/2-ship [kW]	30,72	166,45	220,24	242,83	315,87	394,77
Whole ship grid losses [kW]	61,44	332,9	440,48	485,66	631,74	789,54
Overall ship grid efficiency [%]	**92,87**	**89,37**	**91,59**	**93,33**	**93,30**	**93,19**
Efficiency compared to DC grid [%]	**0,29**	**-0,68**	**-0,53**	**-0,46**	**-0,44**	**-0,70**

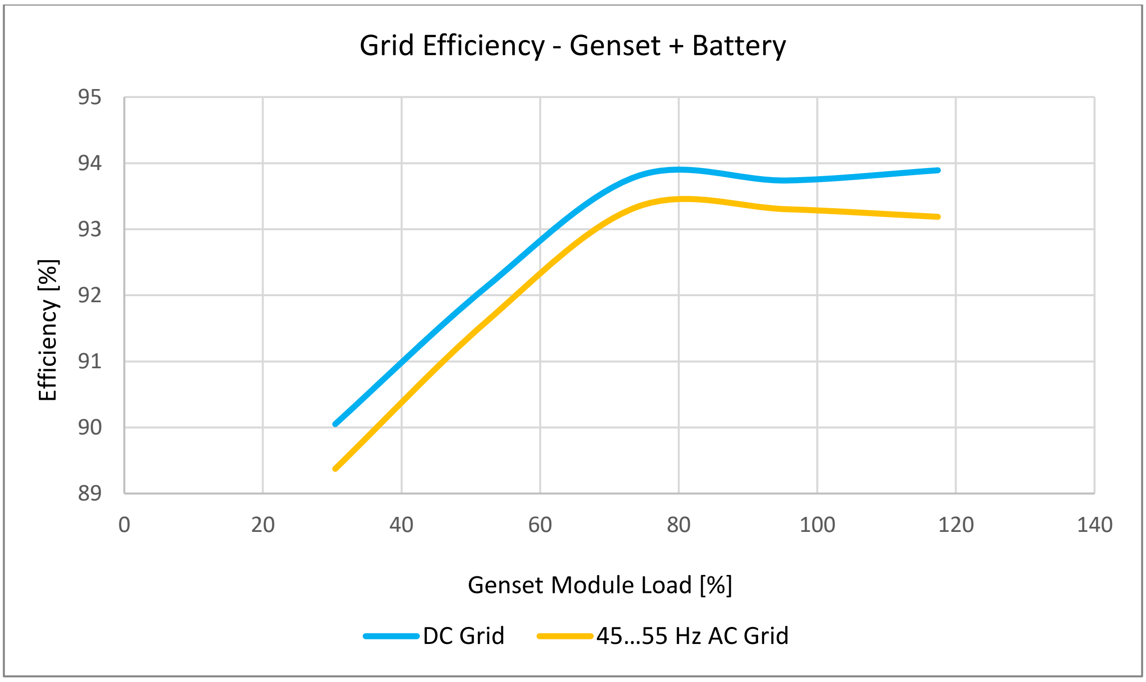

Figure 26. Genset solution - grid efficiency comparison

As contrast, compared with a traditional fixed speed 60 Hz AC grid, the variable frequency AC grid shows a resulting benefit of 1,1…17,0 % in SFOC. Tables 12 and 13 below presents two calculation examples. The variable frequency solution requires an extra stabilizing converter for accommodation and reefer loads. In the first calculation example, presented in table 12, these excess losses are carried by one generator. In the second example, presented in table 13, these excess losses are divided by 4 generators.

Table 12. Comparison of 45…55 Hz vs. 60 Hz grid SFOC for one W16V14

Comparison of 45...55Hz AC and a fixed 60Hz AC setup - 1/2 of a 5+5MW ship - one connected generator									
Generator Load [%]	**11**	**22**	**33**	**44**	**55**	**66**	**77**	**88**	**99**
Load/generator [kW]	126,5	253	379,5	506	632,5	759	885,5	1012	1138,5
SFOC 45...55Hz vs. 60Hz [%]	-18,91	-11,19	-6,06	-3,99	-3,19	-3,09	-3,77	-2,76	-1,98
45...55Hz rpm	1350	1350	1350	1350	1400	1420	1460	1520	1650
Generator voltage [V]	614,25	614,25	614,25	614,25	637	646,1	664,3	691,6	750,75
Conversion Losses Hotel load VFD [kW] (300kW)	11,19	11,19	11,19	11,19	11,19	11,19	11,19	11,19	11,19
Losses due Lower Hotel VFD Input V. [kW] (ref.690V)	0,16	0,33	0,49	0,66	0,66	0,61	0,50	0,00	-1,05
Total excess losses [kW]	11,35	11,52	11,68	11,85	11,85	11,80	11,69	11,19	10,14
Resulting SFOC 45...55Hz vs. 60Hz [%]	**-11,63**	**-7,14**	**-3,17**	**-1,74**	**-1,37**	**-1,58**	**-2,50**	**-1,69**	**-1,11**

Table 13. Comparison of 45…55 Hz vs. 60 Hz grid SFOC for four W16V14

Comparison of 45...55Hz AC and a fixed 60Hz AC setup - 1/2 of a 5+5MW ship - 4 connected generators									
Generator Load [%]	**11**	**22**	**33**	**44**	**55**	**66**	**77**	**88**	**99**
Load/generator [kW]	126,5	253,0	379,5	506,0	632,5	759,0	885,5	1012,0	1138,5
SFOC 45...55Hz vs. 60Hz [%]	-18,91	-11,19	-6,06	-3,99	-3,19	-3,09	-3,77	-2,76	-1,98
45...55Hz rpm	1350	1350	1350	1350	1400	1420	1460	1520	1650
Generator voltage [V]	614,3	614,3	614,3	614,3	637,0	646,1	664,3	691,6	750,8
Conversion Losses Hotel load VFD [kW] (300kW)	2,80	2,80	2,80	2,80	2,80	2,80	2,80	2,80	2,80
Losses due Lower Hotel VFD Input V. [kW] (ref.690V)	0,16	0,33	0,49	0,66	0,66	0,61	0,50	0,00	-1,05
Total excess losses [kW]	2,96	3,13	3,29	3,46	3,46	3,41	3,29	2,80	1,75
Resulting SFOC 45...55Hz vs. 60Hz [%]	**-17,01**	**-10,09**	**-5,25**	**-3,33**	**-2,66**	**-2,65**	**-3,41**	**-2,49**	**-1,83**

As presented in figure 27 below, the differences in efficiency for the DC, variable frequency AC and 60 Hz AC grids are only minor. However, when combined with the ability to use the variable speed Genset for the variable frequency AC and DC grids, the resulting improvement in SFOC is significant. The result is presented in figure 28 below.

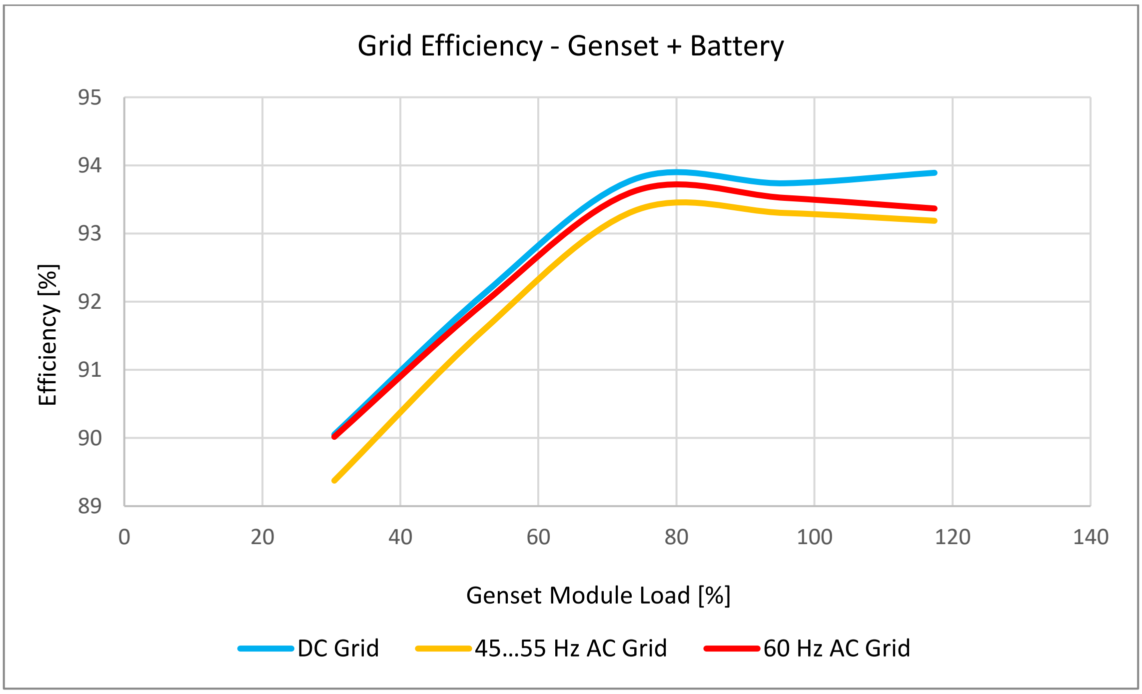

Figure 27. Grid efficiency comparison

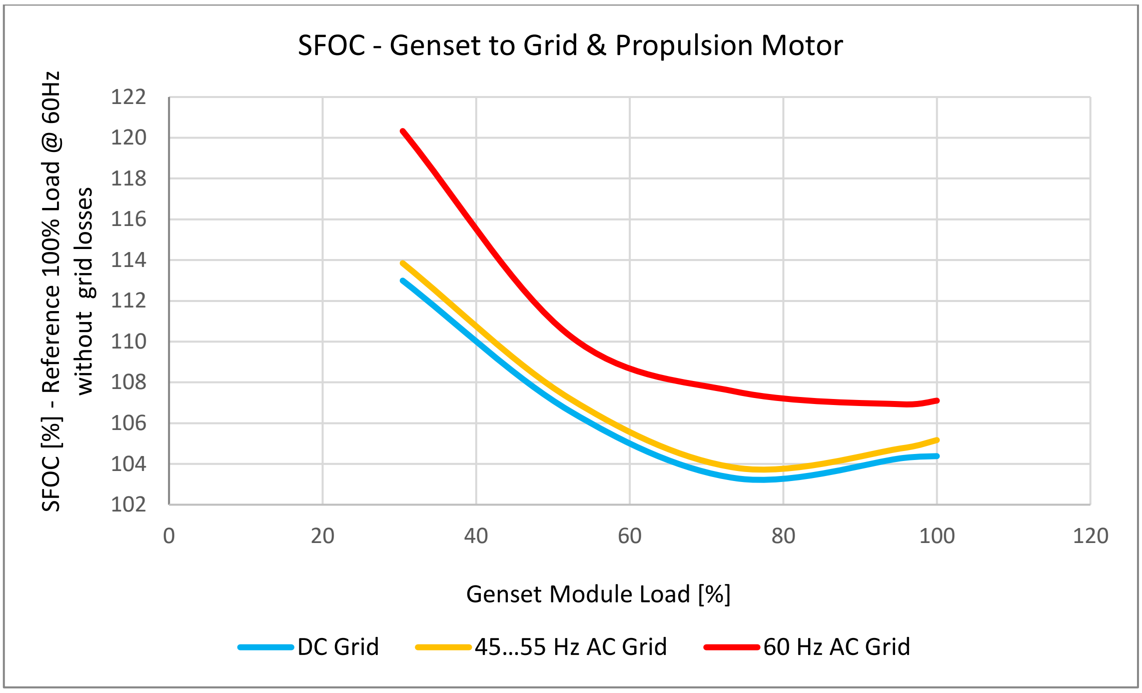

Figure 28. Resulting W16V14 SFOC – Genset to grid and propulsion motor

5.3.2 PEMFC with Battery

The grid efficiency comparison for a PEMFC with peak shaving battery is presented in table 14 and figure 29 below. To present a similar scenario as with the Genset solution, where the peak load is supplied from the battery module, only 24 out of 30 pcs of 200 kW PEMFC modules per grid half are connected.

The DC grid has a natural advantage with the PEMFC solution, as the AC grid need several conversions, where each conversion contributes to the total losses. The results show a benefit of 0,44…2,75% for the DC grid solution.

The dropping grid efficiency at load levels above 50% for the DC grid, and above 70% for the AC grid, are caused by the characteristic dropping output voltage of the PEMFC as the load increases.

Table 14. PEMFC solution - grid efficiency calculation

DC Grid Efficiency - 1/2 of a 5+5MW ship grid - 24x200kW Fuel Cell + Battery						
Connected FC´s [pcs]	3	24	24	24	24	24
Load Hotel [kW]	300	300	300	300	300	300
Load MCC [kW]	100	100	100	100	100	100
Load Main Thruster [kW]	0	1000	2000	3000	4000	5000
Total Load [kW]	400	1400	2400	3400	4400	5400
Load / FC [kW]	133,33	58,33	100,00	141,67	183,33	200,00
Load / FC [%]	66,67	29,17	50,00	70,83	91,67	100,00
Load Battery						600
Losses DC/DC conv./FC [kW]	3,28	2,63	2,60	3,51	4,86	5,86
Losses DC/DC conv./All FC's [kW]	9,84	63	62,4	84,32	116,6	140,64
Losses Battery Conv. [kW]						7,8
Losses PM Converter [kW]		29,85	35,4	33	44	56
Losses Propulsion Motor [kW]		50	80	90	120	150
Drivetrain efficiency [%]		90,74	93,10	94,25	94,01	93,97
Losses Hotel Inverter [kW]	9,19	9,19	9,19	9,19	9,19	9,19
Losses Hotel Transformer [kW]	3	3	3	3	3	3
Losses MCC Inverters [kW]	3	3	3	3	3	3
Total Losses 1/2-ship [kW]	25,03	158,04	192,99	222,51	295,79	369,63
Whole ship grid losses [kW]	50,06	316,08	385,98	445,02	591,58	739,26
Overall ship grid efficiency [%]	**94,11**	**89,86**	**92,56**	**93,86**	**93,70**	**93,59**

AC 45-55Hz Grid Efficiency - 1/2 of a 5+5MW ship grid - 30x200kW Fuel Cell + Battery						
Connected FC´s [pcs]	3	24	24	24	24	24
Load Hotel [kW]	300	300	300	300	300	300
Load MCC [kW]	100	100	100	100	100	100
Load Main Thruster [kW]	0	1000	2000	3000	4000	5000
Total Load [kW]	400	1400	2400	3400	4400	5400
Load / FC [kW]	133,33	58,33	100,00	141,67	183,33	200,00
Load / FC [%]	66,67	29,17	50,00	70,83	91,67	100,00
Load Battery						600
Losses DC/AC conv./FC [kW]	2,27	1,25	1,95	2,78	4,86	7,50
Losses DC/AC conv./All FC's [kW]	6,80	30,10	46,80	66,64	116,60	180,00
Losses FC transformer [kW]	4,00	14,00	24,00	34,00	44,00	54,00
Losses Battery Converter [kW]						12,48
Losses Battery transformer [kW]						4,50
Losses PM rectifier [kW]		23,88	34,12	45,13	56,95	69,39
Losses PM inverter [kW]		29,85	35,4	33	44	56
Losses Propulsion Motor [kW]		50	80	90	120	150
Drivetrain efficiency [%]		91,27	92,44	93,54	92,88	91,96
Losses Hotel Rectifier [kW]	5,1	5,1	5,1	5,1	5,1	5,1
Losses Hotel Inverter [kW]	6,09	6,09	6,09	6,09	6,09	6,09
Losses Hotel Transformer [kW]	3	3	3	3	3	3
Losses MCC Converters [kW]	3,73	3,73	3,73	3,73	3,73	3,73
Total Losses 1/2-ship [kW]	28,72	165,75	238,24	286,69	399,47	544,29
Whole ship grid losses [kW]	57,44	331,5	476,48	573,38	798,94	1088,58
Overall ship grid efficiency [%]	**93,30**	**89,41**	**90,97**	**92,22**	**91,68**	**90,84**
Efficiency compared to DC grid [%]	**-0,81**	**-0,44**	**-1,59**	**-1,63**	**-2,02**	**-2,75**

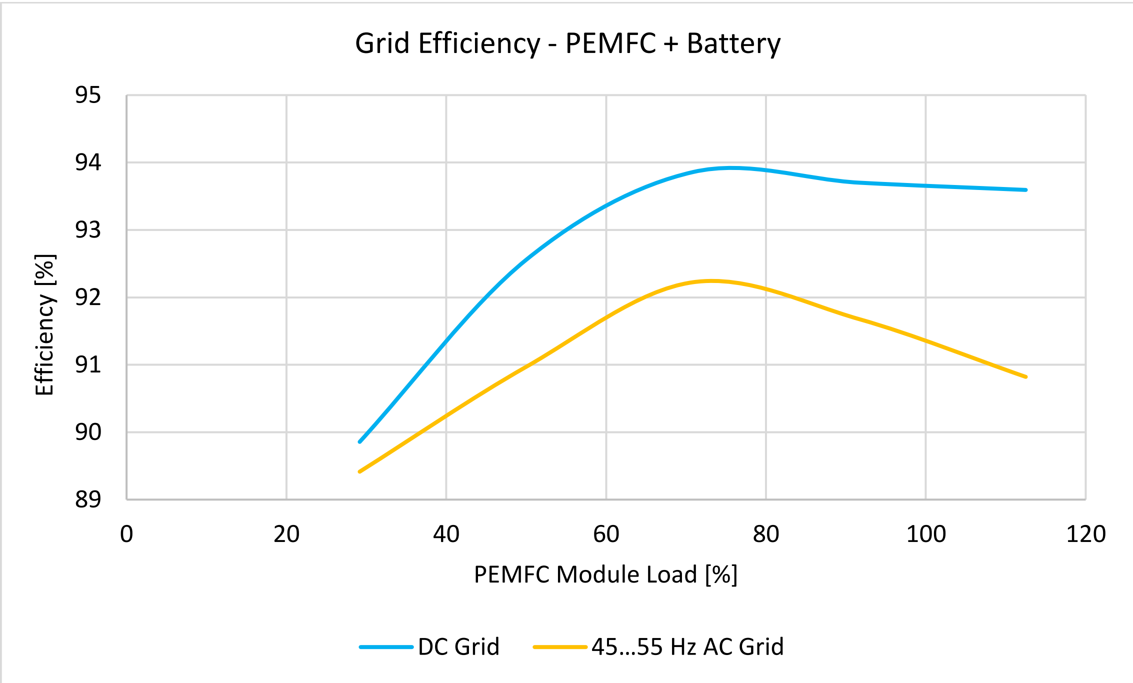

Figure 29. PEMFC solution - grid efficiency comparison

5.3.3 Pure Battery

For the pure battery solution, the DC grid has once more a natural advantage with less conversion steps. The calculations have been done with fully charged batteries. The grid efficiency calculations are presented in table 15 and figure 30 below.

The resulting benefit for the DC grid efficiency is 1,55…4,25%, while the AC grid presents double losses [kW] compared to the DC grid.

The batteries are loaded equally for both grid solutions. The difference in load [%] is due to the limitation of 1500 kW for the AC converter, compared with the 2000 kW for the DC converter. The AC converter has been chosen to 1500kW due to space limitations. Both the 2000 kW DC converter and the 1500 kW AC converter are of frame size CH64.

Table 15. Battery solution - grid efficiency calculation

DC Grid Efficiency - 1/2 of a 5+5MW ship grid - Battery 6x2MWh Battery (Fully charged)						
Connected Battery Units [pcs]	6	6	6	6	6	6
Load Hotel [kW]	300	300	300	300	300	300
Load MCC [kW]	100	100	100	100	100	100
Load Main Thruster [kW]	0	1000	2000	3000	4000	5000
Total Load [kW]	400	1400	2400	3400	4400	5400
Load / Battery Module [kW]	66,67	233,33	400,00	566,67	733,33	900,00
Load / Battery Module [%]	3,33	11,67	20,00	28,33	36,67	45,00
Losses DC/DC conv./BM [kW]	1,67	4,67	6,00	7,93	9,53	10,80
Losses DC/DC conv./All BM's [kW]	10	28	36	47,6	57,2	64,8
Losses PM Converter [kW]		29,85	35,4	33	44	56
Losses Propulsion Motor [kW]		50	80	90	120	150
Drivetrain efficiency [%]		92,85	94,07	95,22	95,21	95,22
Losses Hotel Inverter [kW]	9,19	9,19	9,19	9,19	9,19	9,19
Losses Hotel Transformer [kW]	3	3	3	3	3	3
Losses MCC Inverters [kW]	3	3	3	3	3	3
Total Losses 1/2-ship [kW]	25,19	123,04	166,59	185,79	236,39	285,99
Whole ship grid losses [kW]	50,38	246,08	333,18	371,58	472,78	571,98
Overall ship grid efficiency [%]	**94,08**	**91,92**	**93,51**	**94,82**	**94,90**	**94,97**

AC 45-55Hz Grid Efficiency - 1/2 of a 5+5MW ship grid - Battery 6x2MWh Battery (Fully Charged)						
Connected Battery Units [pcs]	6	6	6	6	6	6
Load Hotel [kW]	300	300	300	300	300	300
Load MCC [kW]	100	100	100	100	100	100
Load Main Thruster [kW]	0	1000	2000	3000	4000	5000
Total Load [kW]	400	1400	2400	3400	4400	5400
Load / Battery Module [kW]	66,67	233,33	400,00	566,67	733,33	900,00
Load / Battery Module [%]	4,44	15,56	26,67	37,78	48,89	60,00
Losses DC/AC conv./BM [kW]	1,73	5,60	8,80	11,79	14,37	17,28
Losses DC/AC conv./All BM's [kW]	10,40	33,60	52,80	70,72	86,24	103,68
Losses BM transformer [kW]	4,00	14,00	24,00	34,00	44,00	54,00
Losses PM rectifier [kW]		23,88	34,12	45,13	56,95	69,39
Losses PM inverter [kW]		50	80	90	120	150
Losses Propulsion Motor [kW]		50	80	90	120	150
Drivetrain efficiency [%]		89,89	90,67	92,00	91,99	91,95
Losses Hotel Rectifier [kW]	5,1	5,1	5,1	5,1	5,1	5,1
Losses Hotel Inverter [kW]	6,09	6,09	6,09	6,09	6,09	6,09
Losses Hotel Transformer [kW]	3	3	3	3	3	3
Losses MCC Converters [kW]	3,73	3,73	3,73	3,73	3,73	3,73
Total Losses 1/2-ship [kW]	32,32	189,40	288,84	347,77	445,11	544,99
Whole ship grid losses [kW]	64,64	378,8	577,68	695,54	890,22	1089,98
Overall ship grid efficiency [%]	**92,52**	**88,08**	**89,26**	**90,72**	**90,81**	**90,83**
Efficiency compared to DC grid [%]	**-1,55**	**-3,84**	**-4,25**	**-4,10**	**-4,09**	**-4,14**

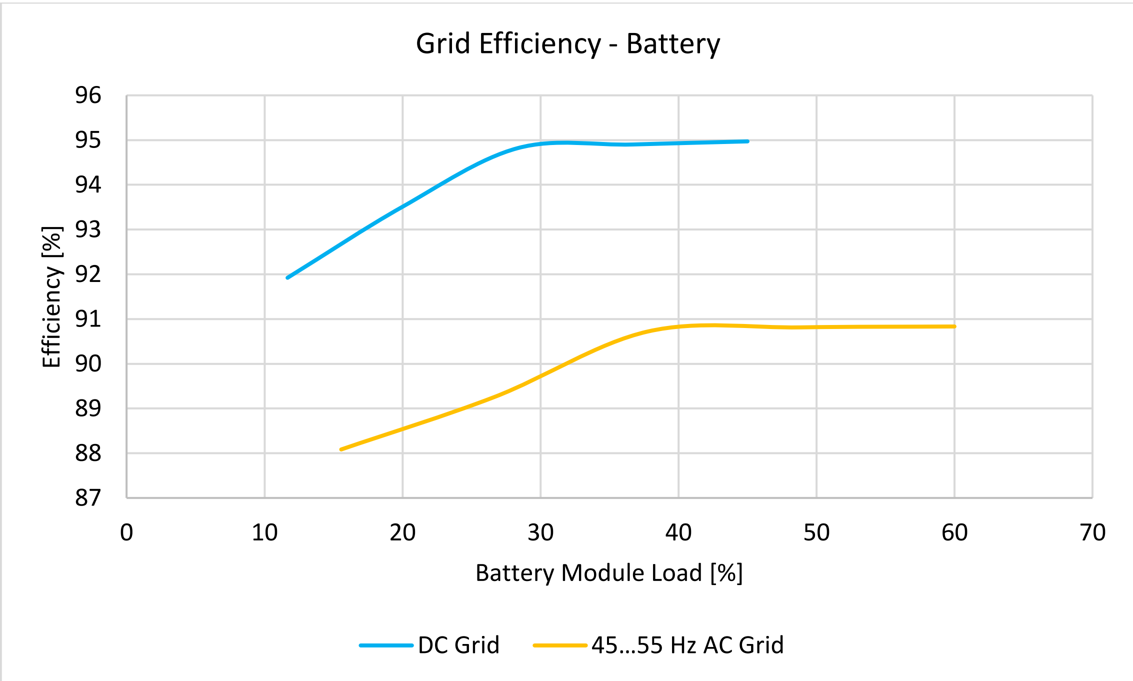

Figure 30. Battery solution - grid efficiency calculation

6 Critical Review and Discussion

If the shipping is to become autonomous or unmanned, the propulsion systems will need to move towards standardized solutions with standardized modules produced in large quantities. These modules need to be easily replaceable to minimize vessel down time. A solution of multiple smaller energy sources gives a natural redundancy, which is essential for reduced or unmanned vessels.

The starting point for this thesis, and the modular energy concept, was to use energy sources installed in standard 40 ft high cube shipping containers. The shipping container benefits of an existing worldwide logistic chain but sets limitations to the energy modules. The investigated energy sources have not been designed for installation in shipping containers whereby the space within the shipping container has not been optimally used. This fact gives the opportunity to improve the energy/power density of the energy modules within the near future.

The calculations of the energy efficiencies are based on values provided by component manufacturers at different load conditions. In discussions with the thesis supervisors, the resulting efficiency levels seem to be somewhat optimistic, but as the main purpose of the thesis is to compare the DC and variable frequency AC grids, the result can be seen as valid. To investigate the differences of the grid designs in more detail, a comparison with a detailed vessel load profile is proposed.

To develop the modular concept, further research is required in the field of mechanical engineering, module space optimization and connector locations. Further investigation is also needed within ship design to find suitable locations for the energy modules. These topics are proposed as new thesis subjects to students interested in the modular design.

7 Summary

The thesis investigated how much of the DC grid benefits the AC grid can achieve, if the frequency is allowed to vary. The comparison of the DC grid and the variable frequency AC grid show a clear advantage for the DC grid. The advantage in energy efficiency is significant, if the source of energy is a PEMFC or purely batteries. The DC grid benefits of lower conversion losses and transfer losses with the investigated setup. The DC grid also benefit of a higher reliability to handle fault scenarios, quicker synchronization and a more flexible connection of additional energy sources, especially DC energy sources. With the DC solution, the grid doesn´t need to be over dimensioned, or compensated, to carry reactive power and harmonics.

The required footprint of the converters, combined with extra transformers required in the variable frequency AC grid solution, also promote the DC grid solution as space and weight are saved. With these factors being evaluated, the DC grid is the proposed grid solution for a modular energy concept.

Interestingly, the variable frequency AC grid show an almost equal efficiency and improved SFOC for a Genset solution as the DC grid. The variable frequency AC grid can thereby be seen as a viable solution for improving vessel energy efficiency with a Genset setup, either with or without a battery for peak shaving and spinning reserve.

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Appendix 1. Wärtsilä V14 Genset main data (Wärtsilä, 2019)

Technical Main Data

The Wärtsilä 14 is a 4-stroke, non-reversible, turbocharged and intercooled diesel engine with direct injection of fuel.

Cylinder bore	135mm
Stroke	157mm
Piston displacement	2,25 l/cyl
Engine displacement	12V - 27L
	16V - 36L
Number of valves	2 inlet valves and 2 exhaust valves
Cylinder configuration	12 and 16, V-engine
Direction of rotation	Counter clockwise
Speed	1500rpm, 1600rpm, 1800rpm, 1900 rpm
Mean piston speed	(7,6 m/s), (8,4 m/s), (9,4 m/s); (9,9 m/s)

Maximum continuous output

Rated output

Wärtsilä 14 engine is produced in 12- and 16-cylinder configurations and the nominal speed from 1500 to 1900 rpm. Power output for mechanical propulsion between 749 and 1340 kWm and for auxiliary generating set and diesel-electric propulsion applications between 675 and 1155 kWe.

CYLINDER CONFIGURATION	12V	16V
Nominal Power (kWm)	749 - 1005	1005 - 1340
Nominal Power (kWe)	675 - 865	900 - 1155
Nominal Speed	1500 - 1900	1500 - 1900

Appendix 2. Ballard FCwave^{TM} main data (Ballard Power Systems, 2020)

PRODUCT SPECIFICATIONS

	FCwave™
Performance	
Rated power	200 kW
Minimum power	30 kW
Peak fuel Efficiency	56 %
Operating voltage	350 - 720 V DC
Rated current [1]	2 x 300 A 1 x 550
System cooling output	Max 65° C
Stack technology	
Heat management	Liquid cooled
H2 Pressure	3,5 - 5 Barg
Physical	
Dimensions (l x w x h) [2]	1220 mm x 738 mm x 2200 mm
Weight (estimate) [3]	875 kg
Environmental protection	IP44
Engine room (DNV GL CG-0339)	+0 °C – +45 °C
Minimum start-up temperature	0 °C
Short-term storage temp	-40 °C – +80 °C
Reactants and Coolant	
Type	Gaseous hydrogen
Composition	As per SAE spec. J2719
Oxidant	Air
Composition	Particulate, Chemical and Salt filtered
Coolant [4]	Water or 50/50 glycol
Safety Compliance	
Certifications	DNV-GL compliant
Enclosure	Hydrogen safe enclosure
Monitoring	
Control interface	Ethernet, Can
Emissions	
Exhaust	Zero-emission

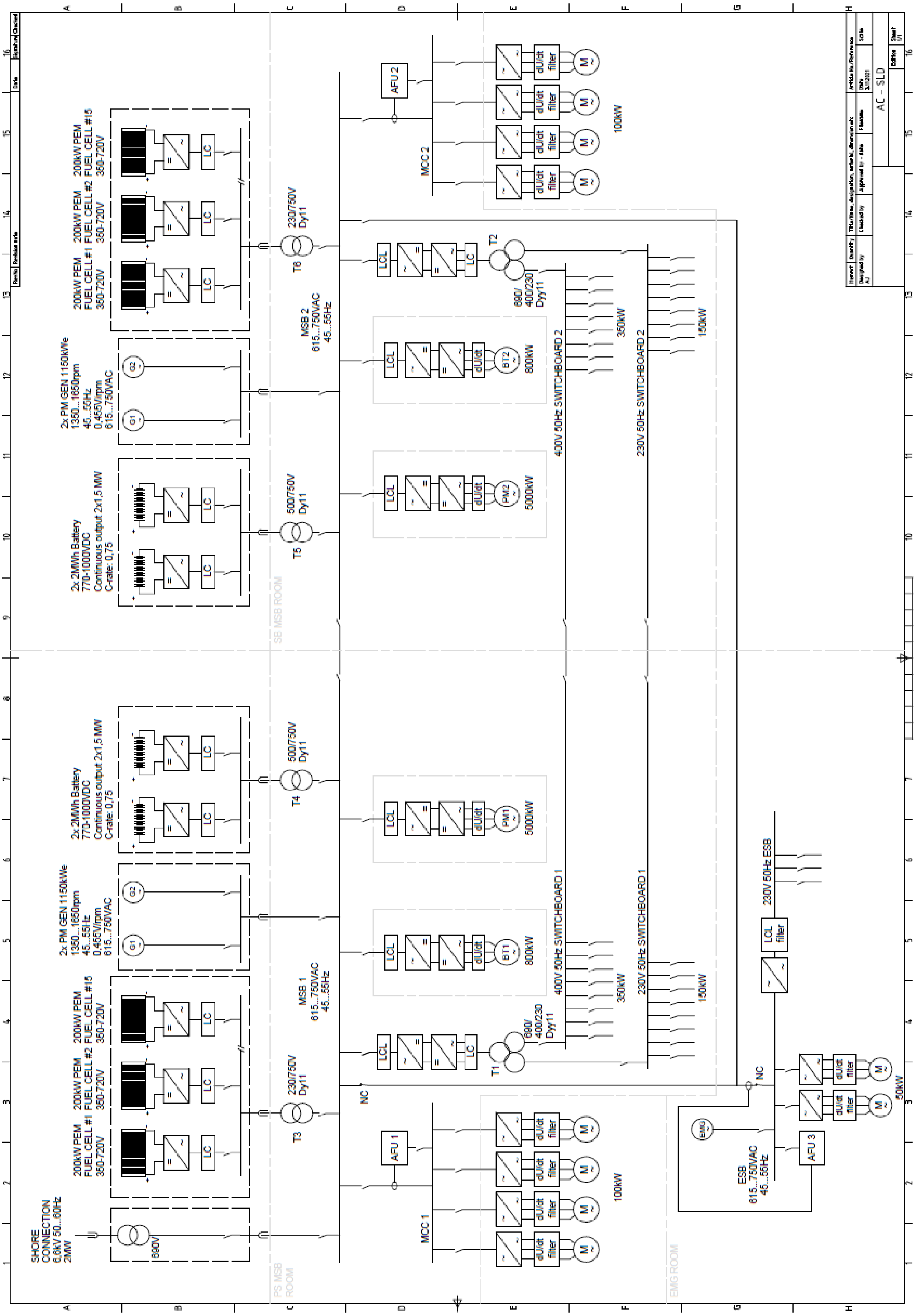
[1] System output is 2 x 300 A (1 x 550A output still under development). [2] Target size. [3] Includes: framed skid base, fuel cell stacks, plumbing and wiring, H2 enclosure, cooling system, air system, electrical panel, and miscellaneous (sensors, cable tray, etc.). [4] Customer coolant type.

Appendix 3. Containerized battery module main data (Shift 2 Clean Energy, 2021)

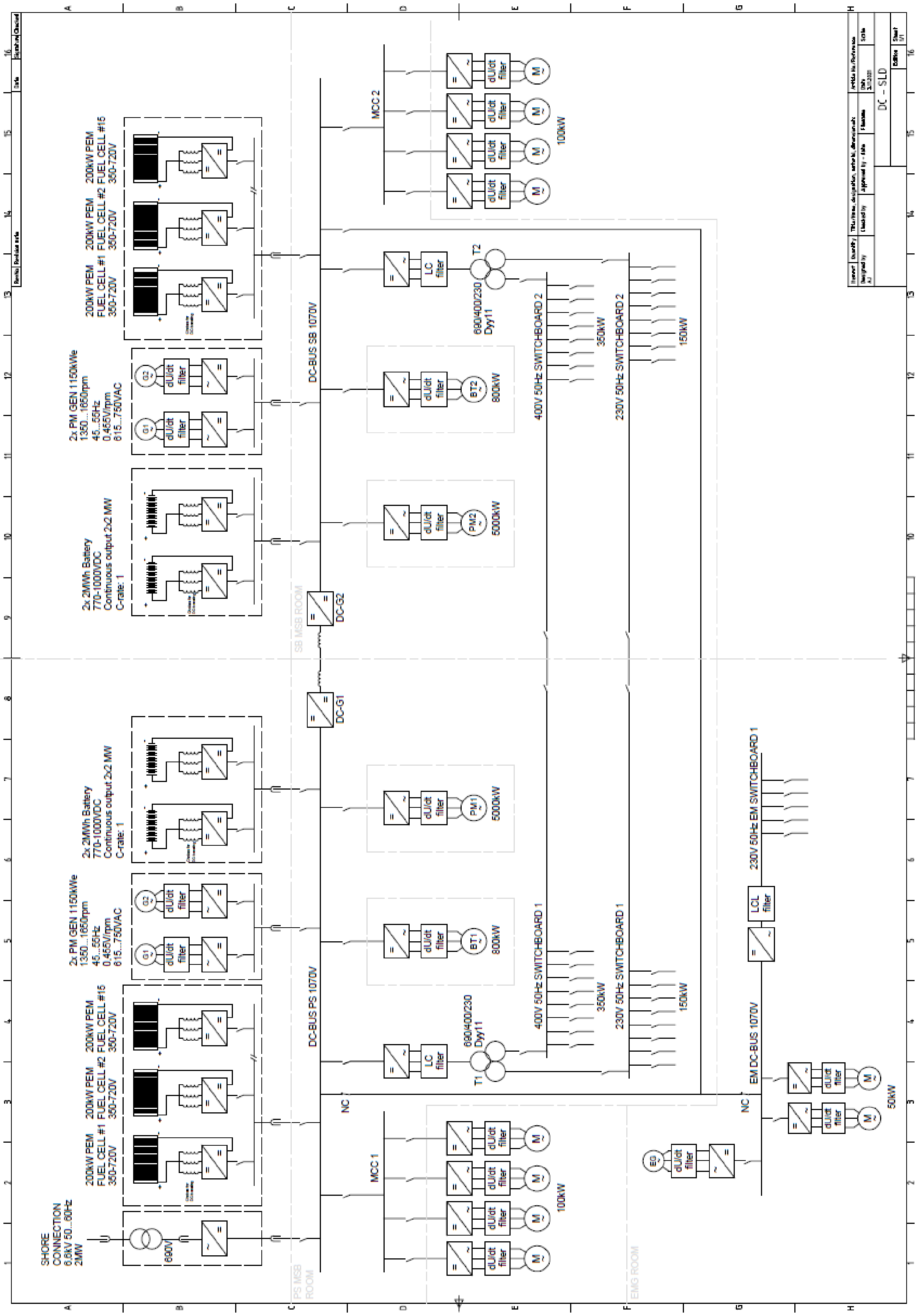
CanPower - Energy 1000VDC Systems
Inclusive Power Electronics

	20ft. Standard Container	20ft. High Cube Container	40ft. Standard Container	40ft. High Cube Container
Energy Storage Capacity	2,200 kWh	2,640 kWh	4,488 kWh	5,456 kWh
Container Format	"20ft. Standard shipping container with 1.5m wide by 0.8m high space added along length of roof top"	20ft. High Cube shipping container with 1.5m wide by 0.8m high space added along length of roof top	"40ft. Standard shipping container with 1.5m wide by 0.8m high space added along length of roof top"	"40ft. High Cube shipping container with 1.5m wide by 0.8m high space added along length of roof top"
Overall Height	3,392mm (134in)	3,738mm (147in)	3,392mm (134in)	3,738mm (147in)
Overall Length	6,056mm (238in)	6,056mm (238in)	12,141mm (478in)	12,141mm (478in)
Overall Width	2,438mm (96in)	2,438mm (96in)	2,438mm (96in)	2,438mm (96in)
Overall Weight*	Approx. 33,000 kg	Approx. 41,000 kg	Approx. 67,000 kg	Approx. 80,000 kg
Lifting Arrangement	By straps, with/without spreader	By straps, with/without spreader	By straps, with/without spreader	By straps, with/without spreader
Cell Technology	NMC	NMC	NMC	NMC
Number of BBUs	125 @ 17.6 kWh each	150 @ 17.6 kWh each	255 @ 17.6 kWh each	310 @ 17.6 kWh each
Number of MBUs	25	30	51	62
System Voltage	1,000 VDC	1,000 VDC	1,000 VDC	1,000 VDC
Voltage per BBU	200 VDC	200 VDC	200 VDC	200 VDC
Battery Cell Type	Energy, 100 Ah	Energy, 100 Ah	Energy, 100 Ah	Energy, 100 Ah
Cell Maximum Charge	Continuous 1C	Continuous 1C	Continuous 1C	Continuous 1C
Cell Maximum Discharge Rate	Rate Peak 2C, continuous 1C	Rate Peak 2C, continuous 1C	Rate Peak 2C, continuous 1C	Rate Peak 2C, continuous 1C
Access	Full Access to battery modules, controllers, and power electronics			
Protection Rating	IP 65			

Appendix 4. Variable frequency AC grid Single Line Diagram (SLD)



Appendix 5. DC grid Single Line Diagram (SLD)



Appendix 6. AC busway (Eta-com, 2015)

Copper

Type	6-7 Cond B x H (mm)	8-9 Cond B x H (mm)	Cross section Area (mm^2)	Busbar Size (mm)	In (A)	Icw (kA)	Ipk (kA)	Rdc 20°C μΩ/m	Rac μΩ/m	X μΩ/m	Z μΩ/m	P Losses @ W/m	Element Weight *Kg/m			
													6 cond.	7 cond.	8 cond.	9 cond.
COPPER CONDUCTOR, Type LB, Single Duct																
LB 08EC	138 x 120	168 x 120	960	2 x 80 x 6	2350	60	132	18	25	19	31	414	56	60	70	74
LB 12EC	138 x 160	168 x 160	1200	2 x 120 x 5	2600	75	165	15	20	13	24	414	73	77	91	96
			1440	2 x 120 x 6	2750	90	198	12	17	14	22	395	78	83	98	103
LB 16EC	138 x 200	168 x 200	1600	2 x 160 x 5	3150	100	220	11	16	11	19	470	93	99	116	122
			1920	2 x 160 x 6	3400	120	264	9	14	11	17	468	99	107	125	133
COPPER CONDUCTOR, Type LB, Double Duct																
LB 08DC	396 x 120	476 x 120	1920	(2)* 2x80x6	4600	100	220	9	13	9	16	794	112	119	140	148
LB 12DC	396 x 160	476 x 160	2400	(2)* 2x120x5	5000	125	275	7	10	7	12	765	145	154	182	191
			2880	(2)* 2x120x6	5400	150	330	6	9	7	11	761	155	166	195	206
LB 16DC	396 x 200	476 x 160	3200	(2)* 2x160x5	6100	150	330	6	8	5	10	882	185	198	232	245
			3840	(2)* 2x160x6	6600	150	330	5	7	6	9	889	199	214	251	265

Appendix 7. Correction factors for busways (Eta-com betobar-r 2000, 2000)

betobar-r

GENERAL LOW VOLTAGE / MEDIUM VOLTAGE
DESIGN FUNDAMENTALS

6. Temperature correction factors

Current t_0 for different ambient temperatures

Peak temperature	°C	20	25	30	35	40	45	50	55	60
Max. daily average temperature	°C	15	20	25	30	35	40	45	50	55
Current rating correction factor		1.18	1.14	1.09	1.05	1.00	0.94	0.88	0.82	0.75

7. Correction factors 60 Hz

Current rating for a power frequency of 60 Hz

betobar-r type	LA03 LA04	LA08 LB08	LA12 LB12	LA16 LB16	SH1 MH1	SH2 PH1	MH2 MH.D	PH1.2 MH2D e
Cu height	30-40	80	120	160	60	100	100	120
Current rating correction factor	1.000	0.988	0.986	0.984	0.984	0.982	0.982	0.980

8. Voltage drop calculation

Generally long busduct connections have to be checked for voltage drop with the following formula :

$\Delta U = \sqrt{3} \times I_s \times a \times L \times (Ra.\cos\phi + X.\sin\phi) \times 10^{-6}$ V.

whereby :

ΔU	= voltage drop (between phases)	[Volts]
I_s	= Normal Full Load Current	[Amps]
a	= current distribution factor	see graph. below
L	= total busduct length	[m]
Ra	= A.C. Resistance at operating temperature*	[∝Ω/m]
cos ϕ	= power factor	
X	= reactance (mean value)	[∝Ω/m]
sin ϕ	= reactive factor (= $\sqrt{1-\cos\phi^2}$)	

* The operating temperature is the sum of the ambient temperature and the temperature rise as a result of the load current. For critical calculations Ra has to be corrected according to the tables (Ra20 or Ra_{85}).

9. Phase sequence

Phase sequence in documentation and product documents :

is indicated as	R	S	T
to be equal to	R	Y	B
or	L1	L2	L3

10. General

For all information or technical calculations, please consult Eta-com or your **betobar-r** agent.

Appendix 8. DC Busway (Eta-com 2, 2015)

LB SERIES

Type	6 conductors BxH (mm x mm)	8 conductors BxH (mm x mm)	6 conductors phase section (mm²)	8 conductors phase section (mm²)	6 conductors In (A)	8 conductors In (A)	Icw (kA)	Ipk (kA)	6 conductors Rdc20 (µΩ/m)	8 conductors Rdc20 (µΩ/m)	P (W/m)	6 conductors weight (kg/m)	8 conductors weight (kg/m)
LB08EC	138x120	168x120	1440	1920	3663	4229	60	132	12,2	9,1	414	56	70
LB12EC	138x160	168x160	1800	2400	4066	4695	75	165	9,7	7,3	414	73	91
LB12EC	138x160	168x160	2160	2880	4399	5080	90	198	8,1	6,1	395	78	98
LB16EC	138x200	168x200	2400	3200	4978	5748	100	220	7,3	5,5	470	93	116
LB16EC	138x200	168x200	2880	3840	5453	6297	120	264	6,1	4,6	468	99	125

Type	12 conductors BxH (mm x mm)	14 conductors BxH (mm x mm)	16 conductors BxH (mm x mm)	18 conductors BxH (mm x mm)	12 conductors phase section (mm²)	14 conductors phase section (mm²)	16 conductors phase section (mm²)	18 conductors phase section (mm²)	12 conductors In (A)	14 conductors In (A)	16 conductors In (A)	18 conductors In (A)	Icw (kA)
LB08DC	138x120	138x120	168x120	168x120	2880	3360	3840	4320	7094	7662	8191	8688	100
LB12DC	138x160	138x160	168x160	168x160	3600	4200	4800	5400	7875	8506	9093	9645	125
LB12DC	138x160	138x160	168x160	168x160	4320	5040	5760	6480	8520	9202	9838	10435	150
LB16DC	138x200	138x200	168x200	168x200	4800	5600	6400	7200	9641	10414	11133	11808	150
LB16DC	138x200	138x200	168x200	168x200	5760	6720	7680	8640	10561	11408	12195	12935	150

Type	Ipk (kA)	12 conductors Rdc20 (µΩ/m)	14 conductors Rdc20 (µΩ/m)	16 conductors Rdc20 (µΩ/m)	18 conductors Rdc20 (µΩ/m)	P (W/m)	12 conductors weight (kg/m)	14 conductors weight (kg/m)	16 conductors weight (kg/m)	18 conductors weight (kg/m)
LB08DC	220	6,1	5,2	4,6	4,1	794	112	119	140	148
LB12DC	275	4,9	4,2	3,6	3,2	765	145	154	182	191
LB12DC	330	4,1	3,5	3	2,7	761	155	166	195	206
LB16DC	330	3,6	3,1	2,7	2,4	882	185	198	232	245
LB16DC	330	3	2,6	2,3	2	889	199	214	251	265

Appendix 9. Minimum required alarms and shutdowns for a hybrid electric system (ABS, 2020, p. 27)

TABLE 4
List of Alarms and Shutdown

Systems		*Monitored Parameters*	*A & D*	*Auto Shut down [1]*	*Notes [A = Alarm; D = Display; x = applies]*
Energy Storage System[3][4]	A1	State of Charge (SOC) – low	x		
	A2	Charging/Discharging - failure	x	x	
	A3	Current – high	x	x	
	A4	Overload	x	x	
	A5	Voltage – high and low	x	x	
	A6	Frequency – high and low (only AC systems) [5]	x	x	
	A7	Cooling or fan - failure	x	x	
	A8	Emergency Stop [2]	x	x	See 5/1.7.iv)
	B1	Cooling medium pressure – low or, temperature – high	x		For subsystem having a cooling system.
	B2	Ventilation - failure	x	x	For subsystem having a ventilation system
	B3	Transformer - failure	x	x	For subsystem having a transformer
	B4	Converter - failure	x	x	For subsystem having a converter
	B5	ESS room or space – high ambient temperature	x		
	B6	ESS (cell, module) – high temperature	x	x	Alternative arrangements can be accepted on risk assessment basis
Shaft Generator	C1	Shaft Generator -failure	x	x	See 4/1.5
Energy Management System (EMS)	D1	Failure System	x		See Table 3 of 3/7.5
Battery Management System (BMS)	D2	Failure System	x		See Table 3 of 3/7.5, if fitted
Supercapacitor Management Systems (CMS)	D3	Failure System	x		See Table 3 of 3/7.5, if fitted
Fuel Cell Control, Monitoring and Safety Systems (FC-CMSS)	D4	Failure System	x	x	See Table 3 of 3/7.5, Section 6/ Table 1 of ABS *Fuel Cell Guide*, if fitted
Power Management System (PMS)	D5	Failure System	x		See Table 3 of 3/7.5, if fitted

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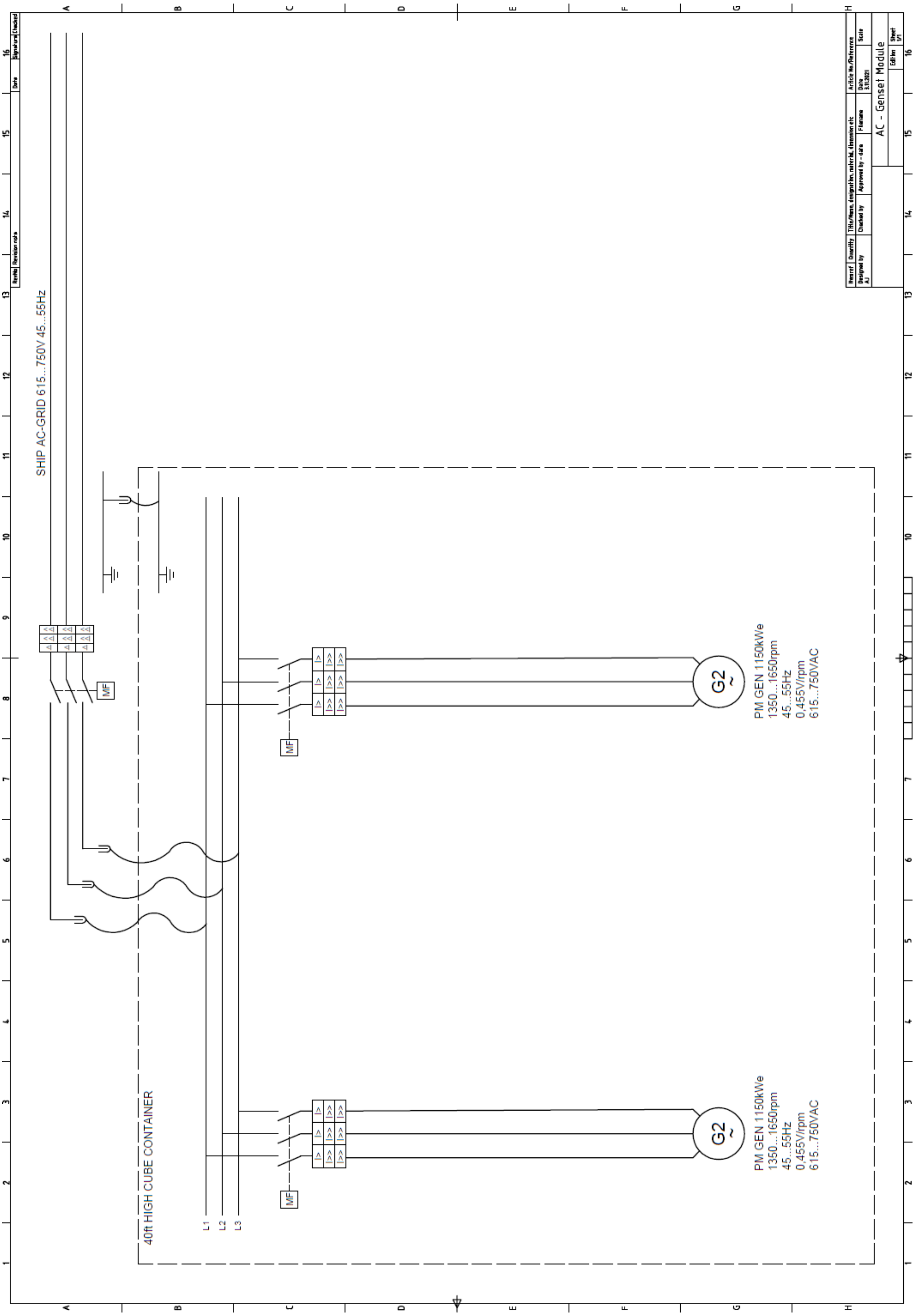
Appendix 10. Alarms and automatic shutdowns of PEMFC installation (ABS, 2019)

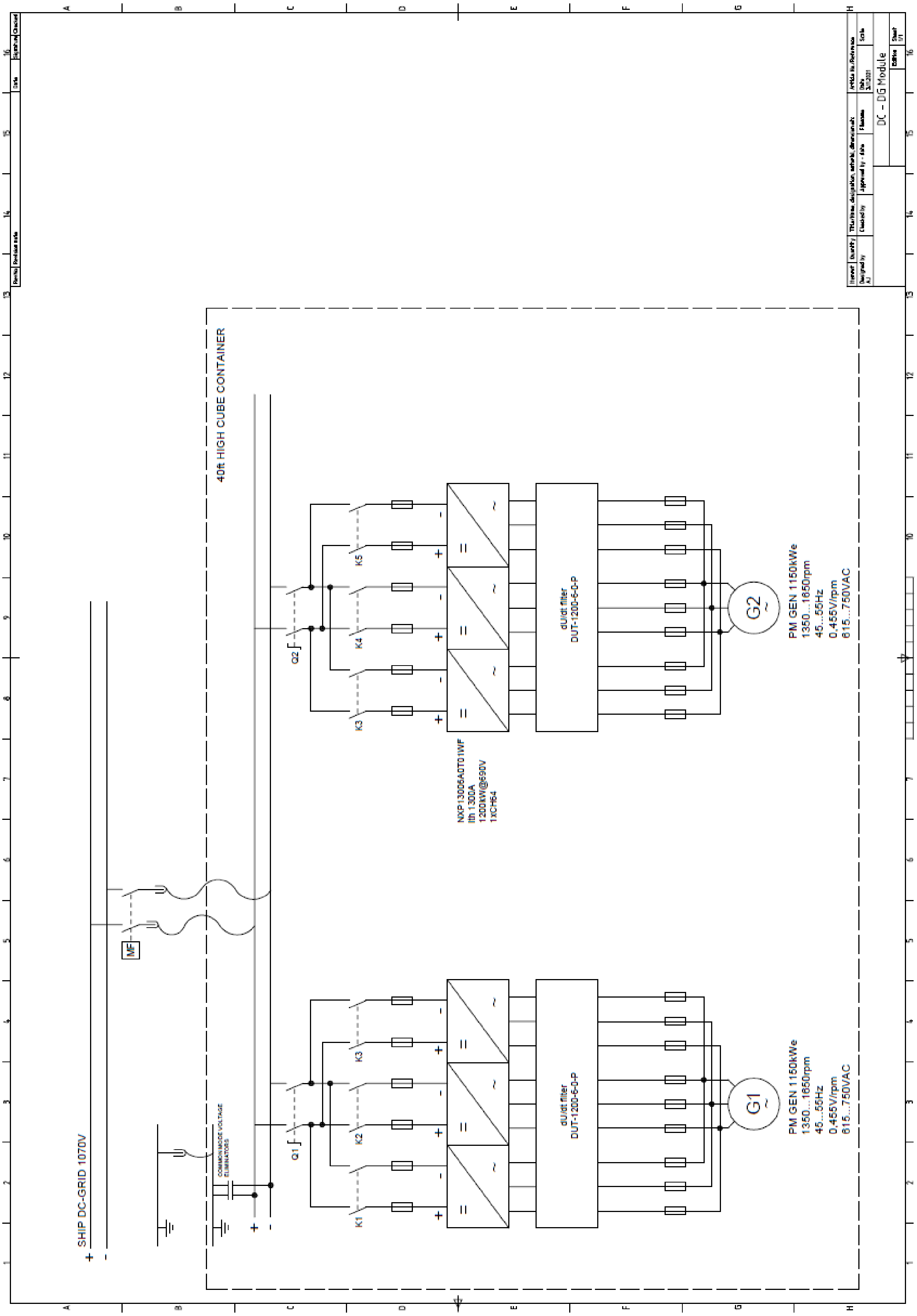
Monitoring of Fuel Cells Power System

Parameter[(1)]	*Alarm*	*Automatic Shutdown of Tank Valve*	*Automatic Shutdown of Master Fuel Valve*	*Automatic Shutdown of Bunkering Valve*	*Comments*
High level fuel tank	X			X	See 6/2.1.1i)
High, high level fuel tank	X			X	See 6/2.1.1ii) & 6/2.2.1i)
Loss of ventilation in the annular space in the bunkering line	X			X	See 6/2.2.1ii)
Gas detection in the annular space in the bunkering line	X			X	See 6/2.2.1iii)
Loss of ventilation in ventilated areas	X				See 6/5
Manual shutdown				X	See 6/2.2.1i)
Vapor detection in cofferdams surrounding fuel tanks. One detector giving 20% of LEL	X				See 6/3.1ix)g)
Vapor detection in crankcase and above stuffing box	X				See 6/3.1ix)e)
Vapor detection in air locks	X				See 6/3.1ix)f)
Vapor detection in cofferdams surrounding fuel tanks. Two detectors giving 40% of LEL[(2)]	X	X		X	See 6/3.1ix)g)
Vapor detection in other area	X				See 6/3.1ix)a), b), c), d) and h)
Vapor detection in ducts around double walled pipes, 20% LEL	X				See 6/3.1vi)
Vapor detection in ducts around double walled pipes, 40% of LEL[(2)]	X	X	X		See 6/3.1vi) Two gas detectors to give min 40 % LEL before shutdown
Liquid leak detection in annular space of double walled pipes	X	X	X		See 6/1.1v)
Liquid leak detection in Machinery space	X	X			See 6/1.1v)
Liquid leak detection in pump-room	X	X			See 6/3.1vi)
Liquid leakage detection in protective cofferdams surrounding fuel tanks	X				See 6/3.1vi)
Fire detection in fuel cell space	X				See 4/5iii)
Air Lock	X				See 3/3.3iv)
Emergency Shutdown	X	X	X	X	See 3/9.6, & 5/5

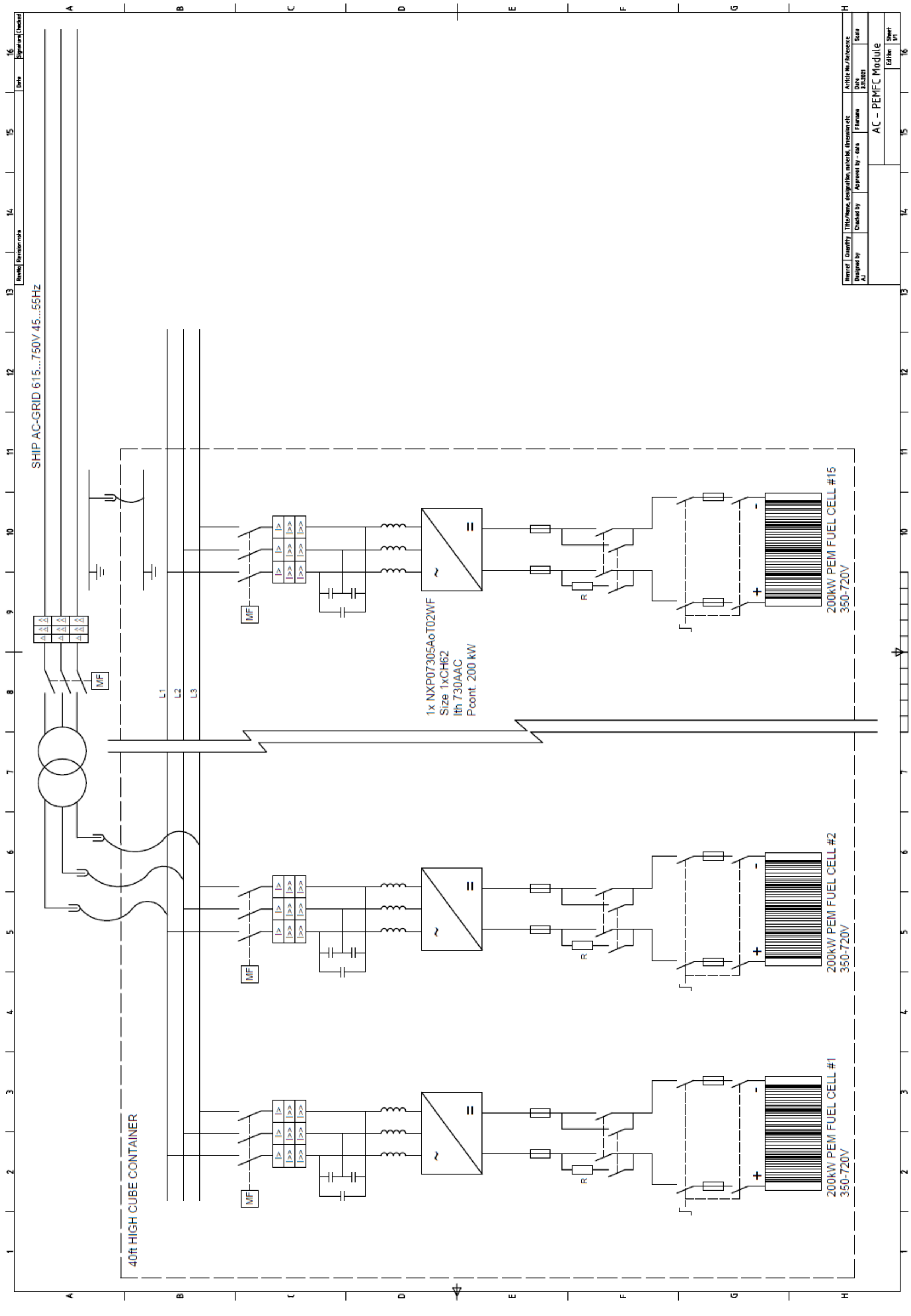
Appendix 11. AC grid - Genset module main diagram



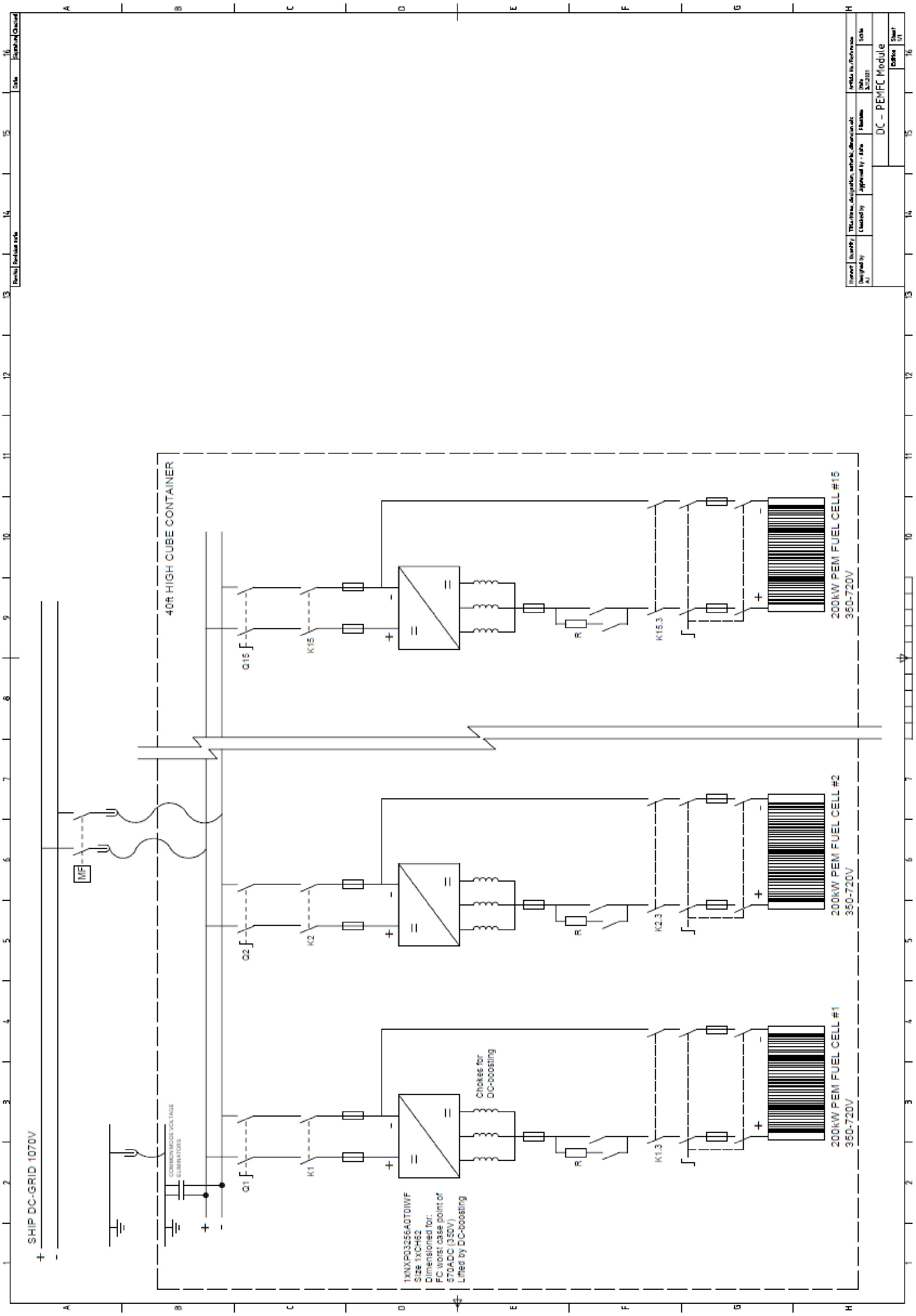
Appendix 12. DC grid - Genset module main diagram



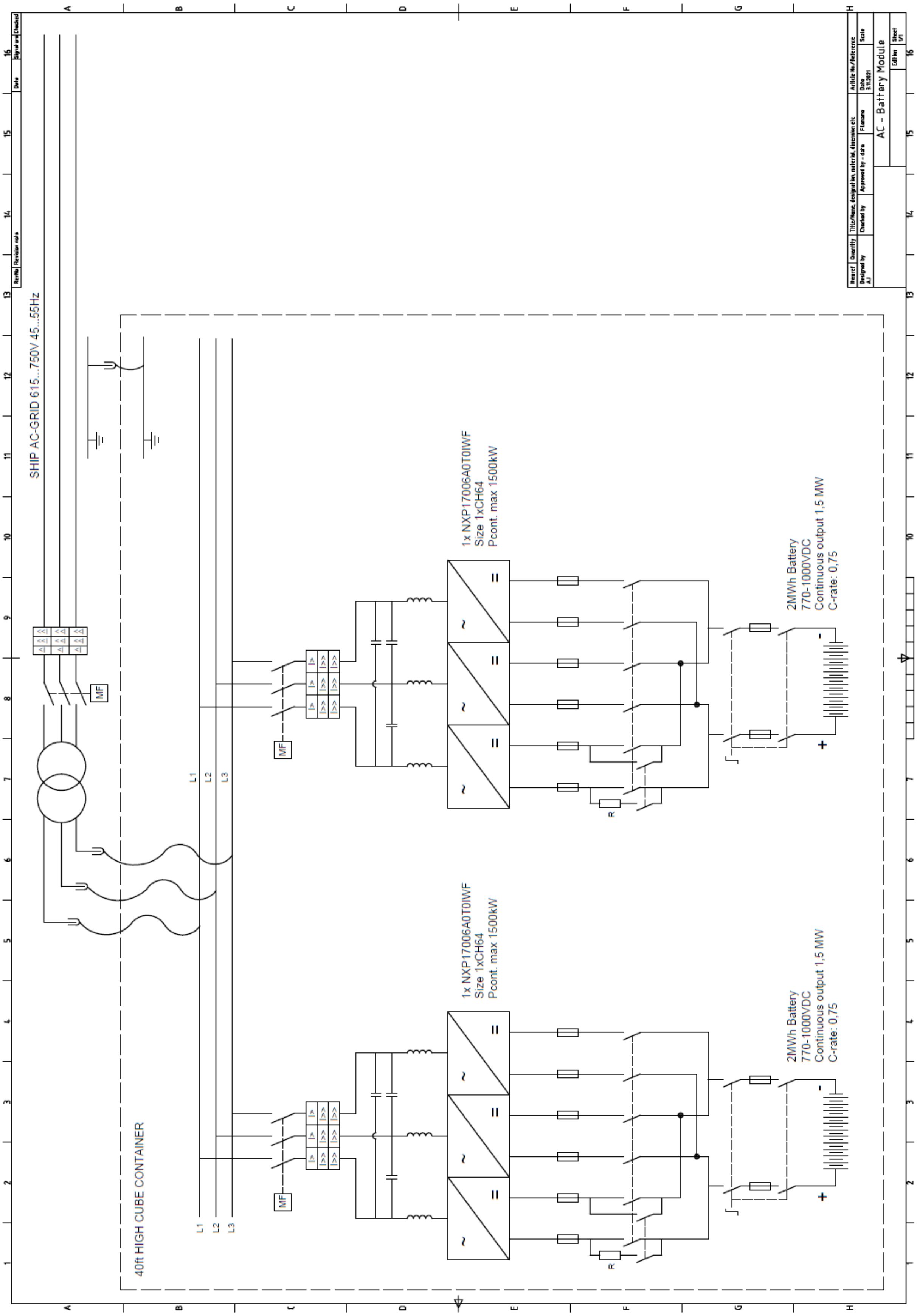
Appendix 13. AC grid – PEMFC module main diagram



Appendix 14. DC grid – PEMFC module main diagram



Appendix 15. AC grid – Battery module main diagram



Appendix 16. DC grid – Battery module main diagram