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Feasibility and Challenges in Microgrids for Marine Vessels

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Preface

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First, my greatest thanks to my supervisor Dr. Ritwik Majumder at ABB CRC who supervises me to work on this interesting topic with continuous help and support. I would like also to express my gratitude to Prof. Dr. Gabriela Hug-Glanzmann, ETH Zürich and Prof. Dr. Massimo Bongiorno, Chalmers University of Technology for enabling this collaboration and kind helps during the scholarship application. Furthermore, I would like to give thanks to Mr. Stavros Karagiannopoulos and Dr. Petros Aristidou for the kind discussions on the project.

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Last but not least, I would like to thank my family for their support throughout my entire studies. They are always there supporting me wherever I am and how far I am away from home.

The fulfillment of this project is a part of the master's degree programme "Energy Science and Technology" at ETH Zürich.

Disclaimer

This report uses ABB's Microgrid Plus System and Marine Solutions as a basis for analysis. Although it uses the functionality from a high level perspective, this thesis does not bare semblance on the performance or the technical functionality of ABB's system and solution. This report is purely conceptual and only takes inspiration from the solutions.

Abstract

Due to the development of distributed generation (DG) and power management technologies, an islanded marine power system, namely microgrid in marine, becomes a promising option for marine power systems and gains an increase in research interest. Microgrid solution provides integration of renewables, energy storage systems and existing generation units. It enhances energy efficiency, reduces CO_2 emissions, and improves dynamic responding to load fluctuations. In this way, the overall performance of vessel information and control system is optimized.

The goal of this thesis is to investigate the feasibility of operating microgrids in marine vessels. Power management strategies are formulated with integration of energy storage and renewable sources, like photovoltaics (PV), to the existing diesel generators within a small-islanded network. Before the system level analysis, modeling of the energy resources, energy storage, and power electronic converters is obtained. In order to weigh the benefits and assess the potentials of implementing the shipboard DC microgrid system, this work facilitates a detailed MATLAB simulation-based study accounting for the factors of realistic vessel operation load profiles, stability and reliability of DC microgrids.

Chapter 1 and 2 provide the introduction and prior art from industrial solutions and academic research. The prior art covers shipboard power network structure, load profile requirement, energy storage system (ESS), power management system (PMS), and academic research methodologies of the marine vessels.

Chapter 3 analyzes the feasibility of implementing a marine microgrid based on ABB solutions of land-based microgrids. An integration of the inland microgrid solutions to the existing marine automation and control platform is proposed. After that, the integrated functions of the proposed marine microgrid are formulated in Chapter 4. The system configuration and the microgrid PMS for marine applications are developed.

Control and energy storage functions and stability of operating the proposed shipboard microgrid system (SMS) are verified in Chapter 5 by testing four specific scenarios. The simulation results show that the SMS works in stable operational modes under various loading conditions. Additionally, with proper power management strategies chosen for different operation modes, the operating of SMS can be shifted between different states without significant impacts on the power quality and stability of the system.

Contents

List of Acronyms

AES	All Electric Ship
PMS	Power Management System
DP	Dynamic Positioning
ESS	Energy Storage System
SOC	State of Charge
VFD	Variable Frequency Drive
SGM	Shaft Generator/Motor
PTI	Power Take-In
PTO	Power Take-Off
DAC	Dynamic AC
IPS	Integrated Power System
WHRS	Waste Heat Recovery System
TEU	Twenty Foot Equivalent Units
VCS	Vessel Control System
ZEDS	Zonal Electrical Distribution System
BUCESS	Battery/Ultracapacitor Energy Storage System
PSO	Particle Swarm Optimization
APHESS	Active Parallel Hybrid Energy Storage System

DG	Distributed Generation
SMS	Shipboard Microgrid System
SPS	Shipboard Power System
WTG	Wind Turbine Generator
SOFC	Solid-Oxide Fuel Cell
FC	Fuel Cell
AE	Aqua Electrolyzer
BESS	Battery Energy Storage System
PV	Photovoltaics
GA	Genetic Algorithm
RTDS	Real-Time Digital Simulator
CRF	Capital Recovery Factor
MOPSO	Multi-Objective Particle Swarm Optimization

ESM	Energy Storage Module
DES	Distributed Energy Storage
EPIC	Electrical Plant and Inverter Controller
PCS	Power Conversion System
AVR	Automatic Voltage Regulator
SES	Static Excitation System
DCS	Distribution Control System

OSV	Offshore Support Vessel
LDP	Low Dynamic Positioning
HDP	Low Dynamic Positioning
AH	Anchor Handling
H	Harbor
BP	Bollard Pull
TT	Transit Towing
TS	Transit Supply
Li-ion	Lithium-ion Battery
MPPT	Maximum Power Point Tracking
CPL	Constant Power Load

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1 Introduction and Prior Art

In this thesis, the feasibility and challenges of operating microgrid in marine vessels are explored. Efficient power management strategies are formulated with integration of energy storage and renewable sources, e.g. PVs, to the existing diesel generators within a small-islanded network. Subsequently, time domain simulations are carried out in MATLAB Simulink platform to validate the main concepts.

The thesis is structured as follows.

Chapter 1 provides the introduction and prior art from industrial solutions and academic research. The prior art covers shipboard power network structure, load profile requirement, energy storage system, and power management system in the marine vessels. The industrial prior art presents marine solutions from technology companies covering control, power management and protection of the electrical network.

The existing proposals for microgrids in marine are presented in Chapter 2. The presented proposals are extracted from academic research including simulation models for marine microgrids, voltage regulation, power sharing, network reconfiguration and sizing of the energy storage device.

Chapter 3 describes the feasibility of implementing microgrid in marine with ABB solutions. First various ABB solutions for energy storage and control are presented. Then, the ABB inland microgrid solution concept is depicted and finally an integration of the inland microgrid solution to the existing marine control platform is proposed. The proposed marine microgrid is capable of integrating the control methods and operational principles required by marine applications.

The integrated functions of the proposed marine microgrid are described in Chapter 4. The system configuration and the microgrid control functions for marine applications are developed. The power management strategies for vessels with renewables, ESS and diesels are proposed for efficient operation under different operational modes.

The time domain simulations are presented in Chapter 5. The system stability is validated under various loading conditions. The concept of power sharing among the energy sources and peak shaving for significant load fluctuations is verified.

The conclusions and scope of future work are presented at the end.

1.1 Introduction to Electrification in Marine, Power Network and Demand of Power Management

The electric ship propulsion has a long history dating back to more than 100 years [1]. In recent decades, the high efficiency of the electric propulsion is achieved through development of semiconductor devices for marine utilizations. Accordingly, the equivalent mechanical solutions are challenged by shipboard electric propulsions. This trend has further driven significant fuel savings. As a result, utilization of all-electric ship (AES) or shipboard integrated power system (IPS) is promoted. Meanwhile, the increasing operation costs and stricter regulations regarding emission problems stimulate the ship designers and operators to follow more energy-efficient ways.

In the early stage, the main electric power source was based on steam turbine technology, and then it is replaced by gas turbine and diesel engine. After that, more and more distributed energy sources can be connected to the shipboard electric grid through converters. In this way, the IPS is configured with distributed energy sources supplying shipboard load demands. Although the shipboard integrated power system equipped with electric power sources can be designed according to the mature principles and technologies of the land-based power plant, it still needs additional considerations due to its islanded scheme.

The common power network operated on the AESs normally comprises IPS, electric propulsion module, and other marine loads [2]. As the shipboard power network is operated as an islanded system, the power system must be configured in terms of safety and the reliability of the generation sources needs to be maintained. Additionally, the stability of operating the shipboard power network should be sustained as well. In modern history, significant development in IT & Automation technology has resulted in increased reliability, integrality, and intelligence of the shipboard power network.

For the purpose of monitoring the operation of AES and supporting operational stability, a power management system (PMS) is functionalized to manage network power flow, regulate voltage level and maintain operation stability. PMS monitors the power plant on a higher level and takes protective measures as load fluctuating and shedding. The PMS controls the shipboard power network through various control strategies, for instance, optimizing the number of online engines and adjusting the load sharing between the generation sources. Some of the PMSs can provide functionalities of protection, condition monitoring and weather forecasting, which increases vessel availability and safety.

All the mentioned PMS functionalities and power system units are mostly stand-alone units, but are in the process of being integrated through system-level communication platform to improve feasibility, stability and reliability [3].

1.2 Common Practice in Marine Power System

In this section, the common practice implemented in conventional marine power system in terms of electric propulsion solution, energy storage system and fault prevention is introduced.

1.2.1 Electric Propulsion Solutions

The electric propulsion solutions for marine today vary depending on vessel types, available technologies and operation profiles. According to ABB vessel segments, offshore vessels, ice-going vessels, passenger vessels, cargo vessels, and special purpose vessels account for the majority of vessels.

For the passenger vessels and some cargo vessels, the electric propulsion system is designed for serving one or two (sometimes three) main propellers ranging up to 20-25 MW. The generator set usually consists of four to six engines. From the maintenance point of view, the engines are normally of the same rating and size. Due to the large shipboard power demand of this segment, the main electric equipment is operating on medium voltage level: 3.3, 6.6, or 11 kV [4].

In terms of the offshore vessels, the dynamic positioning (DP) operation is always of interest. The DP vessels can keep position with thrusters designed for giving maximum thrust at zero knots. In this case, the propulsion load profile fluctuates while the thrust force demanded by the DP control system varies. For this type of vessel, several propeller and thruster units are equipped on both its stern and bow. Five to eight generator engines are usually installed ranging from 1 to 6 MW for each. Depending on the level of vessel´s electrical load, the shipboard power plant is then operated at a medium voltage level, or at a low voltage level [4].

Since ice-going vessels are operated for both navigation in ice and sailing in open water, their shipboard power systems are normally dimensioned with podded propulsion units. ABB introduced Azipod®, a 360° steerable propulsion unit, in 1993 at first for icebreaker vessels. It later becomes an industry standard to use Azipod® on ice-going vessels. The propulsion unit for an ice-going vessel often operates up to 20 MW of a medium voltage electric system [4].

1.2.2 Energy Storage System

Advantages of implementing energy storage system (ESS) are increasingly recognized by the marine industry, due to its ability to improve operational stability, reduce fuel consumptions and eliminate emissions of marine vessels. ESS can be used for regenerating the power produced by the engines, compensating power load fluctuations and smoothing the power extracted from the diesel generation units. Combining with ESS, the propulsion units used for DP are optimized by fostering the dynamic responses of the vessels.

Currently, because of the technology development and cost reduction, the most dominant energy storage devices for vessel applications are batteries, ultracapacitors and flywheels [5]. Batteries are usually suitable for energy-intensive applications because they have higher energy density (kWh/ton) compared to the others (Fig. 1). The runtime of an ESS depends on the energy density of the storage device, Because of that, the ultracapacitors and flywheels can only run up to 1 minute, while the runtime of the batteries can last from 5 minutes to 8 hours. Accordingly, the ultracapacitors and flywheels are proper candidates for short-run but power-intensive applications balancing the power load fluctuations, while the batteries are suitable for medium and long-term supply of power. A fast-acting ESS can compensate for the slow dynamic responses of the diesel generation units and reduce negative impacts on power quality introduced by load variations and transients.

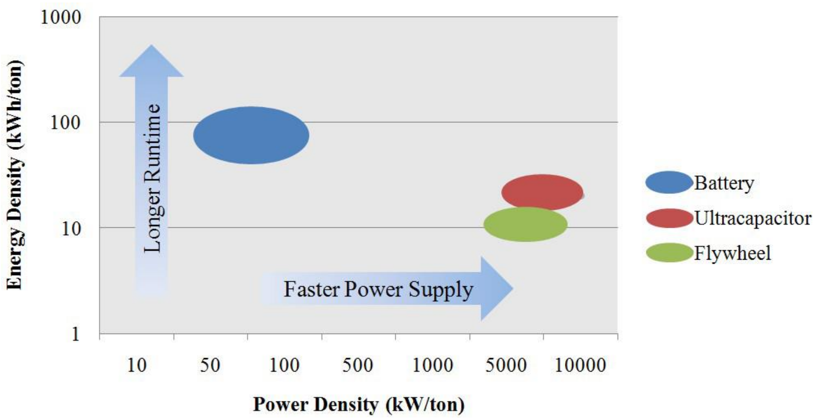


Figure 1: Energy storage devices-[5]

Since the leading battery suppliers, e.g. Corvus Energy and SAFT, start to actively provide marine energy storage solutions with Li-ion battery banks, this type of battery technology is suggested throughout the thesis.

1.2.3 Electrical Fault

Generally, for the shipboard electric network, the neutral point of star-connected generators is not earthed (namely insulated electric network) in the low-voltage distribution, but is earthed through high resistance (namely grounded electric network) in the high-voltage distribution network [6]. The common electrical faults in the shipboard distribution network are Open Circuit Fault, Short Circuit Fault, and Earth Fault [6].

Open circuit fault is usually caused by bad connection or break in a wire. In the case of bad connection, open circuit fault can cause a lot of heat leading to a fire hazard. Short circuit fault occurs when two different phase conductors are connected. Consequently, a large amount of current is released. Failure of insulations and human errors are the examples of the causes of short circuit faults. Earth fault is caused by a connection between a phase conductor and an onboard earthed component.

The insulated electric network continues to supply essential shipboard power services, since the tripping mechanism is not triggered off under a single-line earth fault. Due to this capability of maintaining continuity of power service supply, insulated electric system is normally adopted for low-voltage shipboard electric networks [6].

Sectionalizing the electric distribution network and providing multiple power sources maintain the reliability of a shipboard electric system. The common approaches of maintaining power system reliability are to provide an emergency power system, sub-sectionalize the circuits, and implement selectivity schemes [6]. The protection relays in the switchboard need to make sure that the failures are identified and isolated through a selectivity scheme [6]: under fault conditions, the essential power loads are not interrupted by isolating the defective sections immediately after the faults are identified. The protective elements (e.g. circuit breakers and fuses) corresponding to the faulted sections must then be operating while the protective elements in the healthy circuits do not trip off.

1.3 Power System Solutions from ABB Marine

ABB shows high performance in developing power systems for marine vessels. In the following, solutions initiated by ABB to electrifying the marine vessel operations are presented.

In order to meet the goals of reducing CO_2 emissions, ABB keeps improving existing technologies and searching for energy efficient ways of marine vessel design and operation. According to ABB Marine Energy Efficiency Guide [7], the key to improve marine energy efficiency is to make a sound design combined with power management system and data communication technology. To improve the energy efficiency, increasing the flexibility of a marine vessel is the most cost-effective way [7]. The flexibility can be improved by means of diversifying power generation sources and guaranteeing operational stability under various loading conditions.

There are mainly two types of solutions for ABB shipboard power networks [7]:

- **Consulting services**:
  a) ABB Marine Appraisal is an energy efficiency service. It is a guideline used to make investment decision, in terms of cost and payback time, on energy-saving solutions
  b) Energy Efficiency Audit is a service providing a detailed roadmap for evaluating savings in operational costs of energy efficient practices
  c) Energy Efficiency Training is implemented to raise people´s awareness of energy efficient solutions
- **Technical measures:** specific technologies are selected by vessel segments, and are either for retrofit markets or for new builds (e.g. onboard DC Grid). State-of-the-art marine technical solutions of ABB will be presented in below with more details

1.3.1 ABB’s Advisory Suite [7]

EMMA® Advisory Suite and OCTOPUS® Advisory Suite are ABB’s performance management tools for marine applications. The advisory systems are always integrated with other technical solutions and can be retrofitted freely to enable excellent fit for each vessel type and operation profile. OCTOPUS® Advisory Suite provides vessel motion-based tools, so it monitors the thruster and environmental conditions, which can supply data to PMS under various loading conditions.

The benefits of implementing ABB’s advisory systems can be highlighted as: monitoring and benchmarking fuel consumption for operation process; optimal use of DP system; optimizing power plant for enabling the most economical way to supply load power; providing motion-based tools for increasing vessel availability and safety [7].

1.3.2 Onboard DC Grid [8]

Compared to conventional AC system, a shipboard electric propulsion system configured with DC grid can increase the vessel’s energy efficiency by up to 20% and reduce the number of electrical equipment by up to 30% [8]. Shipboard DC electric network is flexible to integrate different energy sources and optimize component placements. ABB Marine launched Onboard DC Grid concept in 2010, which provides a new solution for low-voltage shipboard power plant. According to ABB Marine’s operation tests, the onboard DC grid can be used for supplying installed shipboard power up to 20 MW with a nominal voltage level of 1000 V DC, and this DC grid configuration obtains a projected 1-year return of investment.

1.3.2.1 Design Principle & Benefits

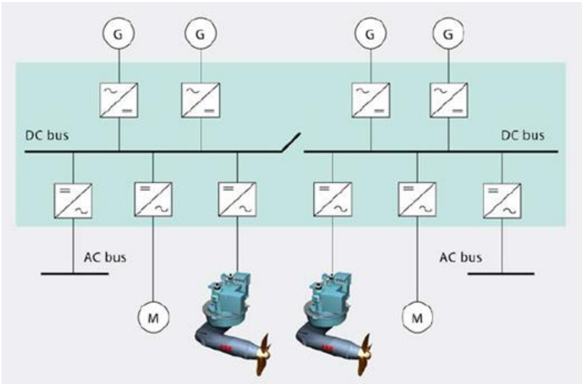
Distributing the power through DC grid reduces the number of switchboard and transformer needed by an AC distribution. This is one of the factors that drive the designers to adopt onboard DC grid. Additionally, in an AC distribution, the grid frequency needs to be maintained, so the diesel generators run at a constant speed and fuel efficiency is declined. In the case of using onboard DC grid, the speeds of diesel generators can be varied to achieve the optimum fuel efficiency.

Most of the ABB generators, motors and drives are well known with proven performance, and these AC-based components can still be plugged into the onboard DC grid through electronic converters or inverters. Because of that, ABB Onboard DC Grid is a platform that enables “plug and play” retrofitting possibilities and adaptability to alternative energy sources. The diesel engine speeds can be adjusted corresponding to the load demands without changing the number of online generators frequently, which increases energy efficiency and operational stability. Furthermore, an expanded application of the onboard DC grid is to integrate it with ESS, so as to compensate the slow dynamic response of the mechanical components and improve DP operation.

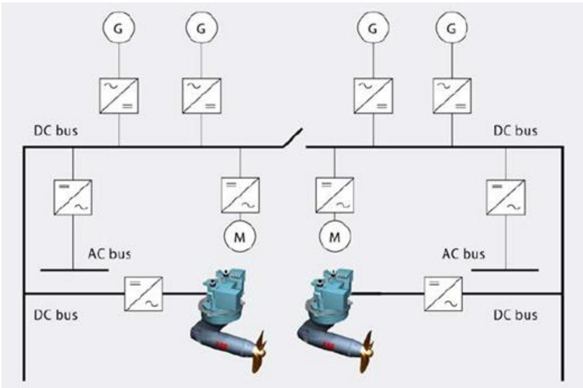
1.3.2.2 DC Grid Configuration

In the DC grid system, all the electric power generated is fed into a common DC distribution bus either directly or through a converter [8]. At this stage, each onboard power source and consumer is controlled and optimized independently. The placement of the electric component is simple and occupies less space compared to the case of AC network.

The configurations of DC distribution grid are normally based on two approaches: a multidrive approach (Fig. 2a) where the converters are all placed within the same location as in the main switchboard of an AC grid, or a distributed approach (Fig. 2b) where each converter is located close to the corresponding power source or load [8].



2a. Onboard DC Grid, multidrive approach



2b. Onboard DC Grid, distributed approach

Figure 2: Onboard DC grid configuration-[8]

1.3.2.3 Protection & Safety

There are some challenges posed for DC distribution grid. Since there is no natural zero crossing for DC current, it is more difficult to be interrupted. Besides, the costs of DC circuit breakers are higher compared to AC circuit breakers.

ABB overcomes the mentioned challenges by introducing a new philosophy. Reliability of the onboard DC grid is achieved by a combination of fuses, isolating switches and controlled turn-off semiconductor power devices [8]. When a fault occurs in a module, the fuses are operated to isolate power electronic modules from the defective parts, and isolating switches of the input circuits isolate the power electronic modules from the main DC bus. The isolating switches are installed in each circuit branch to isolate faulty parts from the healthy sections. In this case, one failure of a load or a generation unit will not affect other suppliers and consumers in the distribution system. In the case of faults on the DC bus itself, the system is primarily protected by means of the isolating switches situated in the circuit branches and the controllable power electronic devices placed in the diesel generators' output circuits.

1.3.3 Hybrid Power Plants Enabled by Batteries [7]

In section 1.2.2, energy storage devices are categorized in terms of energy-intensive use and power-intensive use. Depending on the way of constructing the cathode and utilizing the materials, Li-ion battery can be applied as a high-energy/energy-intensive battery or a high-power/power-intensive battery.

With the functionality provided by Li-ion battery technology, the ESS can run in parallel with other power sources. A hybrid system integrating diesel generators with batteries is now considered as a possible alternative power source for marine application. The basic frame of shipboard microgrid system proposed in Chapter 4 is also based on this concept.

After implementing this hybrid system, the reliability of the marine power system is increased with instantaneous energy backups. In addition, with a proper control strategy implemented, the overall operational efficiency is also increased by smoothing the power consumption under fast and strong load fluctuations. Chapter 4 deals with selection of control strategies and relevant methodologies are presented in details later.

Another question concerned for the onboard DC grid is how to regulate the DC link voltage. One of the approaches maintaining the DC link voltage at a certain level (voltage reference), is to control the AC/DC rectifier. At the same time, the power load sharing/DC voltage regulation is issued.

Load sharing based on voltage droop (Fig. 3) is an effective and robust method for parallel operating power sources (battery and diesel generator in this example). The voltage at the battery terminal varies according to their state of charge (SOC) and charge/discharge current. The natural battery voltage droop curve is referred to as the "cell voltage versus discharge current" (Fig. 4). Without considering the line resistances, the DC voltage is common for both the battery terminal and the AC/DC rectifier.

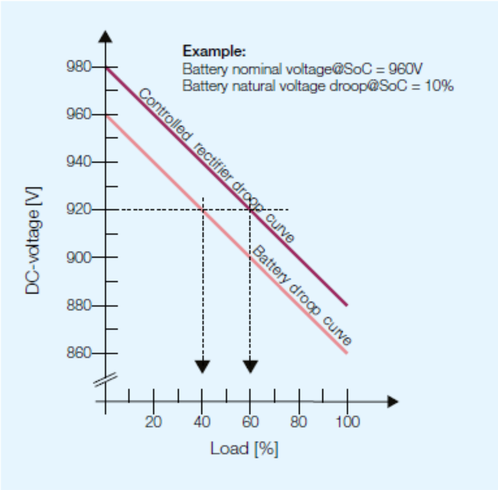


Figure 3: Load sharing between battery and diesel generator-[7]

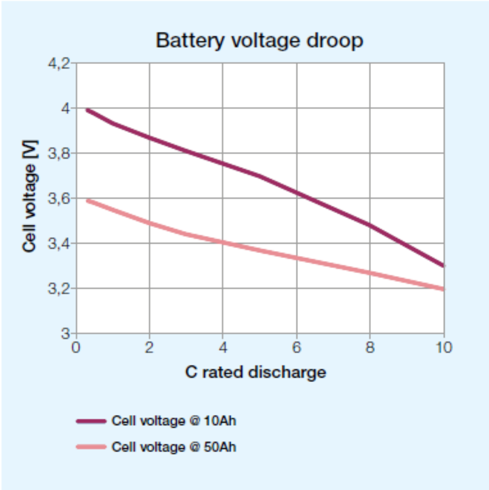


Figure 4: Battery voltage droop curve-[7]

1.3.4 Variable Frequency Drive for Shaft Generator (PTO/PTI) [7]

For a container vessel, it is typically retrofitted to have shaft generators installed to reduce the loading of diesel generator sets. The shaft generators can generate power in parallel with diesel generator sets, or provide all power demands without running the auxiliary engines. With a variable frequency drive (VFD) retrofitted to a shaft generator, the shaft generator can be used on a wider speed range and its operational flexibility is improved [7]. Figure 5 presents a typical system configuration for a container vessel with a VFD installed in the shaft generator/motor system (SGM).

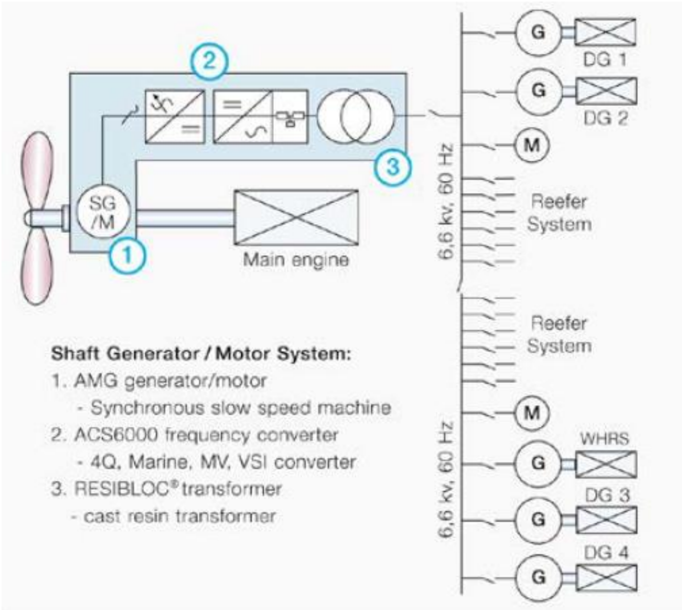


Figure 5: A typical system configuration with a VFD installed in the shaft generator/motor system-[7]

There are mainly three operating modes of a VFD shaft generator/motor system:

- Full electric propulsion: shaft generator works as Power Take-In (PTI) motor (Fig. 6). It can be powered by the auxiliary engines. The main engine can be shut down during low speed operation
- Normal operating condition: shaft generators supply the required electricity load for the vessel entirely by themselves
- Power Take-Off (PTO) mode (Fig. 6): shaft generator/motor is used as an electricity generator when onboard power demand increases. VFD shaft generator/motor system switches to PTO mode to feed power into the shipboard grid

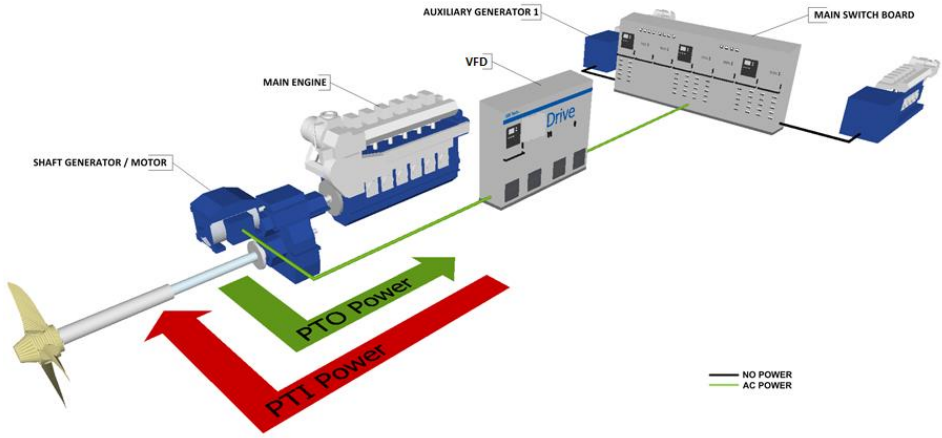


Figure 6: Operating modes (PTO/PTI) of a shaft generator/motor system with VFD-[9]

1.3.5 Dynamic AC (DAC) System [10]

The technology of high-voltage DC grid, which supplies large load demand, is not mature enough to be utilized in large commercial passenger vessels. In addition, a centralized frequency converter is too large and costly to be installed to convert the voltages, which are generated by the variable speed generators, into constant frequency [10]. As a consequence, a concept of dynamic AC (DAC) system is established by ABB.

The DAC concept of ABB can optimize the total fuel consumptions in large vessels by adjusting the rotational speeds of the diesel generation sets. This allows the system frequency to vary within a specified range (Fig. 7). The generators for this concept should be specified to operate within a frequency range, instead of at a fixed frequency level. The magnetic circuits, windings and the other electromagnetic devices need to be dimensioned for being operated under variable frequency conditions.

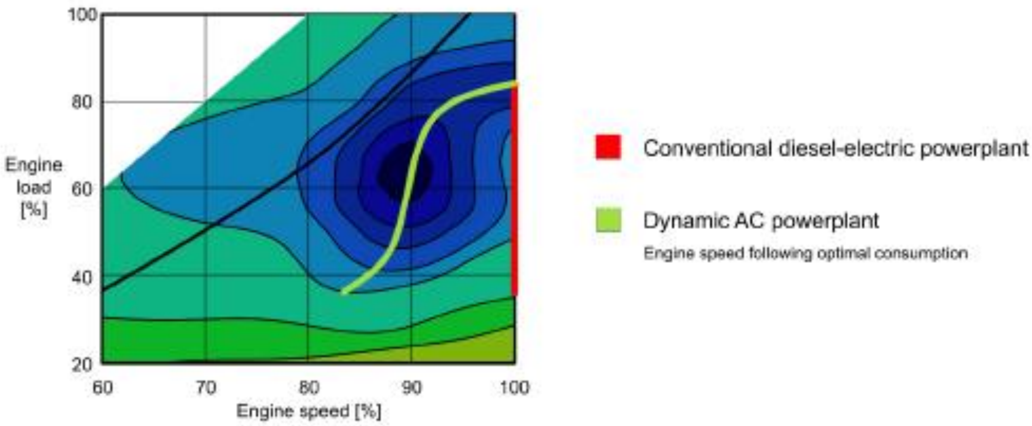


Figure 7: Comparison of specific fuel oil consumption between conventional AC and DAC power plants; source-[10]

1.4 Solutions from Other Industrial Companies

This section introduces the technology developments by various vendors apart from ABB. The main suppliers for marine power systems except ABB are Siemens, MAN DIESEL & TURBO, GE and Rolls-Royce Marine.

1.4.1 Siemens [11]

Siemens BlueDrive PlusC drive solution and Waste Heat Recovery System lead the development of shipboard electric propulsion system. BlueDrive PlusC is a comprehensive solution to diesel-electric vessels and increases safety, cuts operational cost, and decreases the environmental impact [11]. The waste heat recovery system utilizes the heat from exhaust gases to generate steam and produce additional electrical power.

1.4.1.1 BlueDrive PlusC

In 2013, Siemens together with Østensjø Rederi and Corvus Energy delivered an integrated power system (IPS) for the platform supply vessel, Edda Ferd. The ESS in Edda Ferd has a capacity of 260 kWh (40 x 6.5 kWh) and the bus voltage of it is 888 V DC [12]. After that, the Danish ship owner Esvagt chose Siemens' BlueDrive PlusC propulsion system for its two offshore support vessels in 2015. The vessels have four high-speed diesel-generators with a thruster system consisting of two main 1600 kW azimuths, two 1000 kW tunnel thrusters and a redundant fed 880 kW retractable thruster. All thrusters are frequency controlled by BlueDrive PlusC [13].

The variable speed diesel generator plays a crucial role in the BlueDrive PlusC system. This type of generator enables the engines to run within the optimal speed range. The shipboard power network is prepared for connections to renewable energy sources and ESS. This can lead to a significant reduction of fuel consumption and CO_2 emission.

Additionally, BlueDrive PlusC system also integrates Siemens' leading automation technology, SIMATIC. It is used for onboard power management system to monitor generators' speeds and output voltages, track the vessel's power demands, and manage DP operations [11]. Siemens SIMATIC shares some similar functionalities with ABB Advisory Suite.

1.4.1.2 Waste Heat Recovery System (WHRS)

Siemens Solution of shipboard WHRS is a heat-to-power electric propulsion system usually for cargo vessels. Since a WHRS regenerates power from the exhaust gases, it cuts vessel energy costs and reduces the CO_2 and NO_x emissions of the vessel as well. PMS imbedded in the WHRS ensures a safe and reliable operation performance at any time. Figure 8 shows an overview of a WHRS.

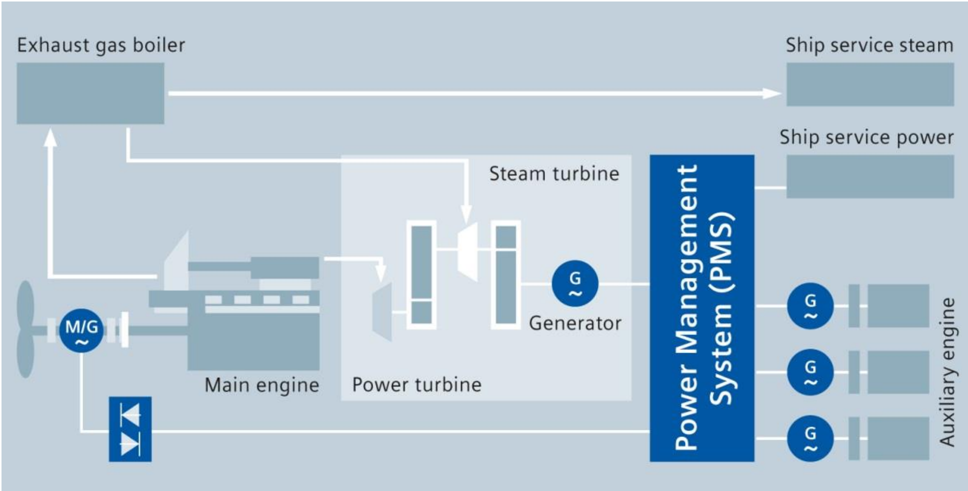


Figure 8: An overview of Siemens waste heat recovery system for vessel-[14]

1.4.1.3 SISHIP EcoMain

Siemens Solution for Shipping (SISHIP) delivers an automation control system for vessel management. EcoMain is involved in SISHIP portfolio and collects data from all relevant onboard systems of an entire fleet, so as to provide a platform for vessel performance evaluation (Fig. 9). EcoMain's uniformed database can also be accessed from onshore, which enables a comprehensive review and analysis throughout entire fleet. Data provided by EcoMain can be used for efficiency improvement, environmental compatibility, trouble-shooting and remote maintenance [11, 13]. Maersk Triple E Class container ships are integrated with Siemens VFD-based WHRS as well as EcoMain system [15].

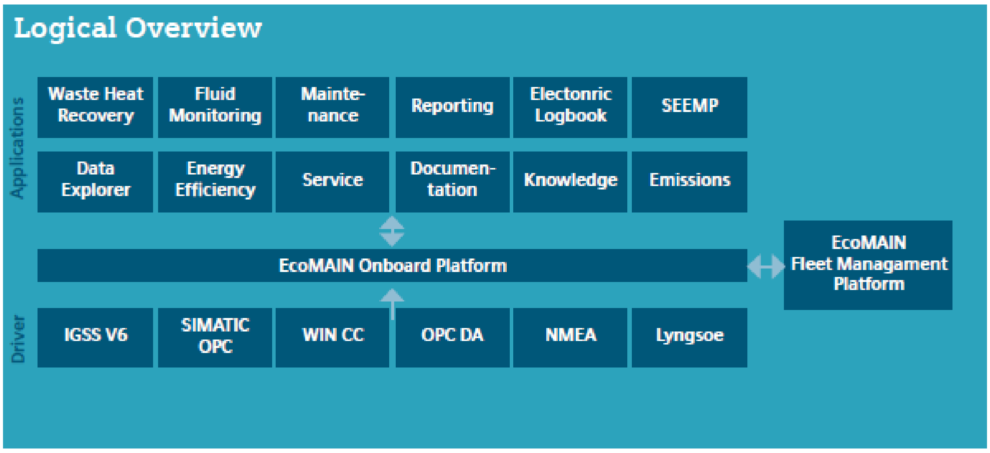


Figure 9: A logical overview of EcoMain system-[13]

1.4.2 MAN Diesel & Turbo [16]

The energy from the main engine exhaust gas is attractive among the waste heat sources of a ship is because of its large heat flow and high temperature. By implementing WHRS, fuel reductions of between 4 ~ 11% are possible [16].

MAN Diesel & Turbo is a large engine designer and manufacturer. It has been involved in some research and feasibility studies on WHRS. According to its studies, an onboard WHRS significantly contributes to reducing emissions, ship operating costs and the newly adapted energy efficiency design index (EEDI).

1.4.3 GE [17]

GE Global Offshore & Marine offers solutions for marine business worldwide. Based on "heat-to-power" principle, Echogen Power System is introduced with a specialty of using CO_2 as the working fluid. Besides, optimization of dynamic positioning operations and vessel automations are realized by SeaStream™ DP System and Latest C-Series Vessel Control System respectively.

1.4.3.1 GE New Power Take Off/Power Take In (PTO/PTI) Technology [18]

The contract with Maersk Line marks GE Global Offshore & Marine enter into the **container ship** industry [18]. Like some other competitors, GE also proposes a solution based on SGM. PTO/PTI solution is provided by GE to Maersk Line for eleven 2nd generation triple-E vessels. With a capacity of 19630 TEU for each, it is comprised of a SGM installed between the main engine and the propeller. This solution consists of two drives, two induction asynchronous motors and a PMS. The electrical energy converted from the vessel drive shaft is then extracted to where it is needed. In this way, it is not necessary to burn fossil fuels to power these systems.

1.4.3.2 Exhaust Energy Recovery System: Echogen System [19]

GE provides Echogen Power Systems to deliver efficient heat-to-power plants for the marine vessels. Echogen is a closed loop system using CO_2 as the working fluid to convert exhaust energy into electricity, with an approximate system efficiency of 50% [19]. The properties of CO_2 ensure a more compact, more efficient and cheaper waste heat recovery system.

1.4.3.3 SeaStream™ DP System [20]

SeaStream™ DP system enhances efficiency and safety of the DP operations. It provides flexibility for effective maritime DP operations. It is an energy-efficient marine system to reduce operational costs and emissions. It is fully integrated and configured for optimizing electric propulsion performance.

1.4.3.4 Latest C-Series Vessel Control System (VCS) [21]

The Latest C-Series Vessel Control System is a centralized monitoring, automation and control system providing fully remote services. A coherent system is obtained by implementing the VCS which integrates and unifies the sub-systems on an individual vessel. As a result, machinery monitoring, automation control and power management are carried out via the latest C-series .

1.4.4 Rolls-Royce Marine

Rolls-Royce marine is an experienced marine technology and service producer. Its UT 700-series for platform supply vessel is recognized as a worldwide benchmark within the offshore industry [22].

Rolls-Royce marine promotes IPS in recent years. The IPS with SAVe label is configured for vessels with energy saving systems [23]. The SAVe Safe system is an example of Rolls-Royce marine's IPS. The number of generators installed depends on the total shipboard power requirements or the vessel operating profiles. When power demand gets reduced, some engines can be turned off.

As a conclusion of analysis on solutions from industrial companies, table 1 presents a summary of the mentioned industrial companies' products and applications. The trend in the marine industry is moving towards to heat-to-power solution, automation of vessel information and control system, and integrated power systems. In terms of shipboard integrated power systems, Siemens and Rolls-Royce are the most active players among the competitors of ABB.

	Application & Product	Partnership	Vessel Type
Siemens	BlueDrive PlusC	Østensjø Rederi and Corvus Energy Edda Ferd (2013)	Platform supply vessel
		Danish Esvagt	Offshore support vessel
	Waste Heat Recovery System (WHRS)	UMM SALAL, United Arab Shipping	Container vessel
	SISHIP EcoMAIN	Maersk Triple E Class Ships	Container vessel
MAN Diesel & Turbo	Waste Heat Recovery System (WHRS)		
GE	New Power Take Off/Power Take In (PTO/PTI)	Maersk Line **2nd generation** Triple-E	Container vessel
	Exhaust Energy Recovery System: Echogen		
	SeaStream™ DP Systems		
	Latest C-Series Vessel Control System (VCS)	S.A. Agulhas II	Icebreaking polar supply ship
Rolls-Royce Marine	Integrated Power Systems (IPS) SAVe label SAVe Safe System	UT 700-series Industrial Standard	Platform supply vessel
ABB	Onboard DC Grid System	Dina Star (2013)	Platform supply vessel

Table 1: Summary of competitors' products/applications

1.5 Academic Prior Art

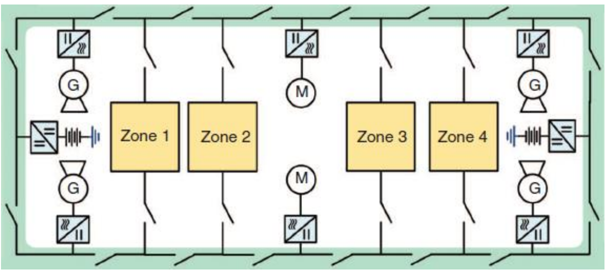
Some of the academic prior arts of marine power systems are presented in this subchapter. They investigate on grid configurations, fault protections, hybrid battery/ultracapacitor ESS and VFD-based control. Most of the methodologies provided in the studies are focused on developing individual component, independent module or local control topology, but system-level control, holistic communication and power management strategy have not been discussed extensively at this stage.

1.5.1 Shipboard DC Grid Configuration

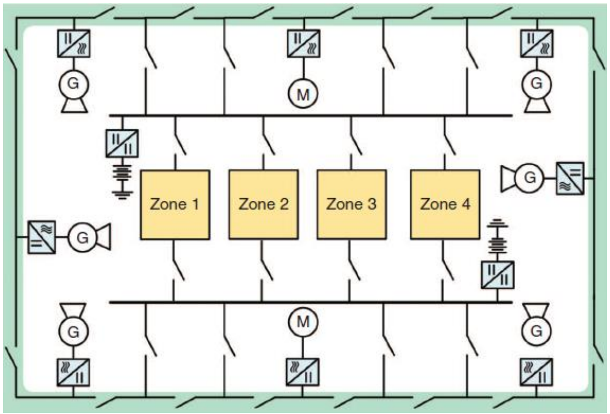
According to the advantages of using shipboard DC grid aforementioned, utilization of a shipboard DC distribution network is focused in this thesis.

Zheming Jin and *Giorgio Sulligoi* propose an optimized configuration of AES featuring onboard DC network [3]. Figure 10 demonstrates a ring-bus DC gird configuration designed for the crucial loads with higher security requirements.

Onboard DC grid configuration, especially the ring bus, obtains more compact structure compared to AC grid, which fits the size and weight requirements predefined by the structure of the vessel.



10a. Single-ring-bus DC distribution



10b. Dual-ring-bus DC distribution

Figure 10: Typical power architectures of ring-bus based DC distribution systems-[3]

The reliability of the system is sustained by implementing specific fault solutions. In figure 11, the switches around the ring bus are deployed to isolate faults that may occur at the buses. The ring-bus-based distribution system on marine vessel under *Zheming Jin* and *Giorgio Sulligoi*'s study is named as zonal electrical distribution system (ZEDS). It should be noticed that the onboard loads in the zones are fed from both sides of the ship. As shown in Fig. 11, the restoration mechanism of the ZEDS is based on self-healing method. After a success in isolating a fault, the power converters of the healthy buses are reenergized to allow the effective sections to be operated normally. For the dual-ring-bus DC distribution (Fig. 10b), the system applies different current levels on the two buses that are connected to the loads with high power quality on the inside and lower power quality on the outside. Solid state circuit breakers may be able to isolate faults for the dual-ring-bus DC configuration.

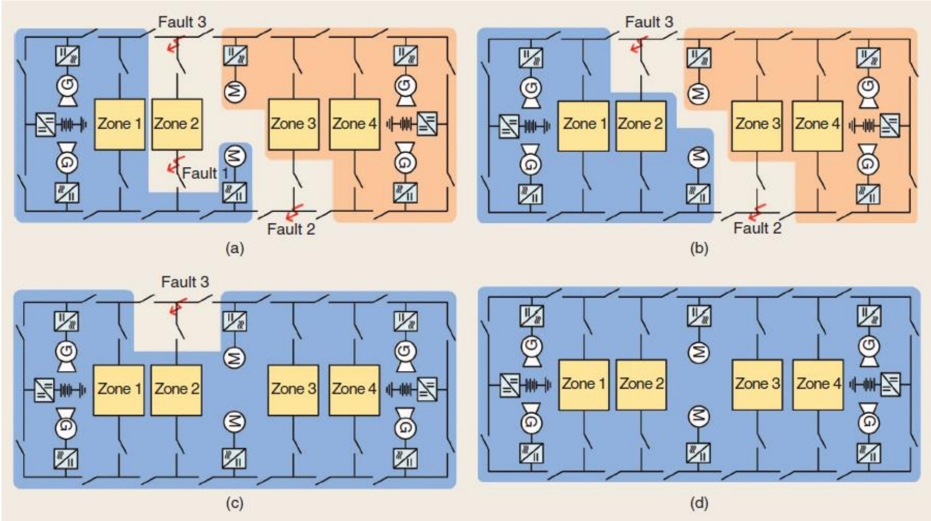


Figure 11: The process of sectionalization and reconfiguration based on the self-healing method: (a) faults occur, (b) fault1 clear, (c) fault2 clear, and (d) fault3 clear-[3]

1.5.2 Optimal Loading Condition of Hybrid Power System

Bijan Zahedi and *Lars E. Norum* conduct a detailed efficiency analysis of a shipboard DC hybrid power system [24]. The power system under investigation consists of four generation units, propulsion loads, auxiliary loads, and an energy storage system configured by Li-ion battery and full-bridge bidirectional converter (Fig. 12).

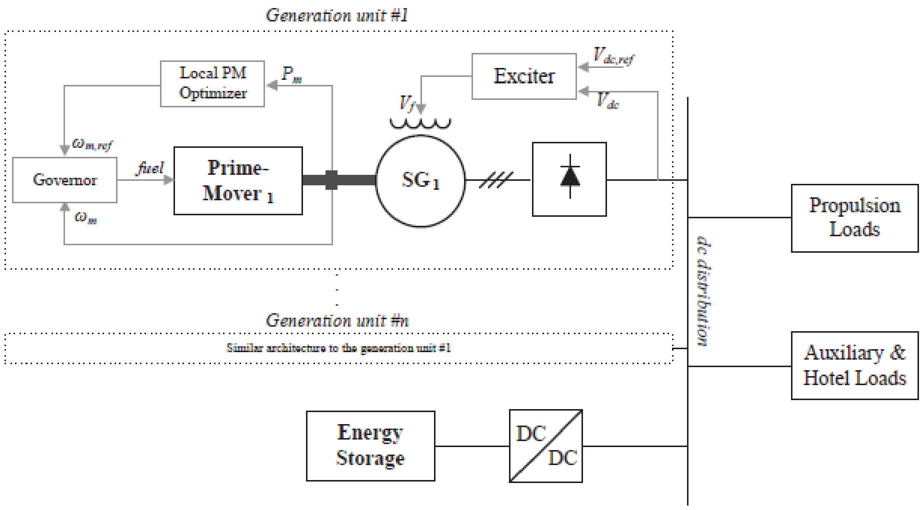


Figure 12: The investigated shipboard DC power system-[24]

A local control system in the generation unit including a local prime-mover optimizer and a governor is implemented to control the rotational speed of each prime mover. In terms of managing power sharing among the generators, controllers based on voltage droop are used to coordinate all the exciters of the diesel engine systems. The bidirectional DC/DC converter of the ESS enables charging and discharging the battery in a locally controlled manner. The proposed ESS operates at a continuous mode or a periodical charge/discharge mode. It is observed that under continuous mode the DC source operates with constant number of engines defined for each operating mode, and in the case of periodical mode, the DC energy source works with variable number of online diesel engines.

In order to achieve an energy-efficient system, the optimal loading conditions are found with the purpose of minimizing fuel consumption. However, the power quality**,** in terms of the DC link voltage level, of this proposed hybrid power system is not tested.

1.5.3 Pulse Load Compensation with Hybrid Battery/Ultracapacitor

Battery and ultracapacitor combination systems applied for future land vehicles have been broadly explored, but similar applications in shipboard electric systems need to be further studied. *Yichao Tang* and *Alireza Khaligh* verify the feasibility of Hybrid Battery/Ultracapacitor energy storage system for naval applications [5]. A 500 V to 1 kV Battery/Ultracapacitor Energy Storage System (BUCESS) is designed for a 100 ~ 500 kW propulsion system. For both charging and discharging modes, feasibility of 100 kW transmission capacities for batteries and 1 MW for ultracapacitors is investigated.

In the research of *Yichao Tang* and *Alireza Khaligh*, the DC-distribution power system of a navy ship has two dc voltage levels: one is high voltage level (between 4.7 kV and 10 kV) and the other is medium voltage level (between 700 V and 1 kV). The medium voltage level is implemented mainly for critical loads like energy storage system. Batteries can charge ultracapacitors through a bidirectional converter and another converter realizes the transmission between DC bus and batteries. Similar scheme is utilized for 1 MW charging and discharging of ultracapacitors. The batteries and the ultracapacitors are also capable of being combined to discharge at the same time.

This paper verifies the feasibility of applying the proposed BUCESS for pulse load compensation, but further analysis on system-level transient behavior when the operational profile changes or pulse load occurs is needed.

1.5.4 Pulse Load Compensation with Flywheel and Prime Mover

Mahdi Saghaleini and *Behrooz Mirafzal* set up a concept of Regenerative Energy Management for pulse-loads in dual DC-AC microgrids [25]. Pulse loads can cause voltage sags and degrade the system stability. In this work, with the consideration of pulse loads, it demonstrates an approach that can be executed to regulate the voltage level of a DC-bus in the power distribution network. Kinetic energies of flywheels and motor drives, e.g. prime movers, on an electric ship are used in the proposed method.

Figure 13 presents the proposed system. To some extent, the whole power network can be used to feed the pulse loads in addition to the flywheel. The technical challenge lays in the fact that the impacts of the pulse loads are easily leaked to the network. In order to eliminate the impacts, the prime mover of the shipboard power system works as the main compensator of the pulse loads, and the flywheel motors are used to suppress the fluctuations caused by the variations of the prime-mover (a huge motor) speed.

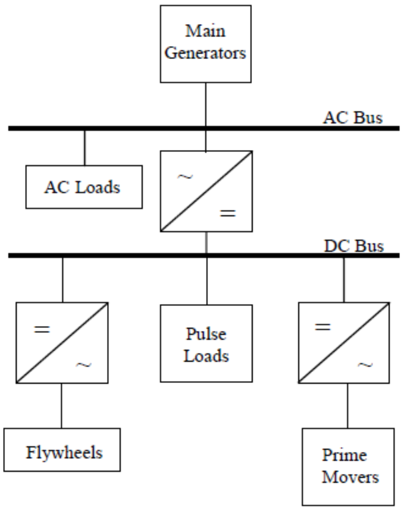


Figure 13: A regenerative energy management for pulse-loads in dual DC-AC microgrid-[25]

1.5.5 Energy Management Strategy for Load Variation

As discussed before in section 1.3 and 1.4, ABB and some other technical companies in marine industry have done some research on VFD-based applications, in order to compensate the load variations and reduce fuel oil consumption. *Spyridon V. Giannoutsos* and *Stefanos N. Manias* optimize energy management and diesel fuel consumption in marine power systems through VFD-based flow control [26].

This energy flow management strategy is applied as retrofit installation in a typical tanker vessel's power system. Experimental results are compared to the previous operating conditions without retrofitting, so as to verify the effectiveness of the optimization.

Four engine room ventilation fans and one CSW pump in the tanker vessel are retreated with the proposed system. Under various operating load demands, the energy management system calculates optimal number of online diesel generators based on the proposed topology. In this way, annual diesel fuel consumption is reduced especially during water-going period with main engine running at low speed (55% ~ 60% of rated speed).

Note that this work proposes a feasible approach for optimizing the onboard fuel consumptions, but the reliability and stability of using this system when there are significant changes in different operational modes are not verified. Thus, problems could occur when it is implemented on offshore support vessel that often requires dynamic positioning operations.

1.5.6 Stabilizing Power Fluctuation with Energy Storage System

In the previous studies of *Yichao Tang* and *Mahdi Saghaleini*, the regulation approach against power volatility is set up for the pulse loads (e.g. weapons) in the shipboard power system instead of considering the propulsion load fluctuations. The pulse loads can be controlled via forecast, but due to the complex marine conditions, the propulsion load fluctuations cannot be predicted that easily. Accordingly, in [27], hybrid energy storage is implemented to keep the propeller's speed constant and compensate propulsion load fluctuations.

Jingnan Zhang and *Qiang Li* propose a method for stabilizing the power fluctuation of the shipboard electric propulsion system, and establish a dynamic simulation model of the integrated system [27]. In this energy management strategy, battery combined with a super capacitor is considered as a hybrid energy storage system. The hybrid energy storage capacity is optimized using Particle Swarm Optimization (PSO) algorithm. At the same time, the active parallel hybrid energy storage system (APHESS), including two levels of charge and discharge controller, establishes a local control function to enable the energy storage system generating precisely and responding promptly to the load fluctuations.

The load fluctuation is studied according to a LNG ship's experience. Figure 14 shows the topology of the shipboard power system under study. This electric propulsion system implements an AC-DC-AC converter to control the propulsion motor M. Pulse load is connected to the AC bus through a rectifier, and the hybrid energy storage unit (Li-ion battery with super capacitor) connects to the system via a DC/DC converter.

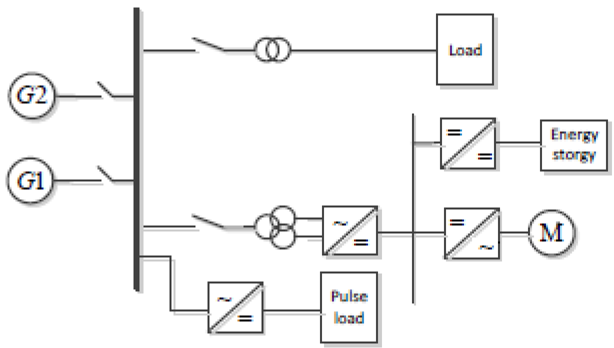


Figure 14: A simplified integrated shipboard power system-[27]

In order to obtain an optimized capacity of the hybrid energy storage unit, PSO algorithm is used. Furthermore, the APHESS is designed to carry out a real-time adjustment and stabilization for output power fluctuations.

The objective of the optimization problem is to minimize the configuration cost of the storage system. Operation characteristics of the Li-ion battery and super capacitor, operation constraints of the generators, and variations of system power loads are considered as complementary conditions. Detailed equations can be referred to [27].

In terms of the local energy storage control, an APHESS is set up with two levels of bidirectional DC/DC converters (Fig. 15).

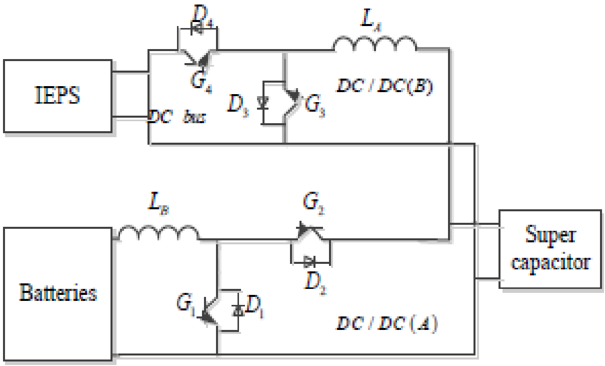


Figure 15: APHESS topology-[27]

When the sum of generators' output power is greater than the maximum power set point, APHESS will be controlled to release power. On the other hand, when the DC bus voltage increases due to load demand decreases, the energy storage system is controlled to absorb power from the system. As a consequence, the total power reserved in APHESS can be distributed flexibly between the batteries and super capacitors through this control strategy.

This study of *Jingnan Zhang* and *Qiang Li* provides a simple prototype of shaving the propulsion load peaks, but operational windows of the generation units need to be investigated and optimized. Moreover, since the realistic loading profile is more complex than the test case defined in this study, consideration regarding the power flowing properties and functionality of the proposed hybrid energy storage system need to be expanded.

As a summary for Chapter 1, it first presents the solutions, from both ABB and other industrial companies, of electrifying the marine vessel operations based on the common practice implemented in the existing marine power systems. After that, some of the academic prior arts of marine power systems are introduced. Most of the methodologies aforementioned are concentrated on developing individual component, independent module or local control topology, but system-level control, communication and power management system for a network have not been discussed extensively in this chapter.

In Chapter 2, a literature review is conducted regarding to different topics that are investigated in this thesis. This overview of theoretical research methodologies and mechanisms lays a foundation for developing actual system design, control and energy storage concepts of this thesis.

2 Literature Review – Microgrid for Marine

In this chapter, some theoretical research methodologies and mechanisms proposed in academic literatures are investigated. This overview lays a foundation for developing the actual concepts of this thesis. First, a definition of a microgrid is presented with an extension to scheme of microgrid for marine. After that, the current framework, theoretical knowledge and academia prior art within the area of microgrid for marine are reviewed to analyze the possibility of implementing and adopting these research methodologies and mechanisms.

2.1 Microgrid and Microgrid for Marine

The ABB definition for microgrid refers to operating distributed energy resources and loads in a controlled and coordinated manner. The generation units and loads can optionally be connected to the utility grid or operate in "islanded" mode. Microgrid solution can be enhanced via advanced power network control and various power management strategies. Due to the development of distributed generation (DG) and power management technologies, an isolated or islanded power system, namely microgrid in marine, becomes a promising option for marine power system and gains an increase in research interest. In other words, a shipboard power system is, in every extent, a microgrid because it contains DG, power network control, and loads within an islanded frame. It is an isolated and self-sufficient power system in the sea. Note that this thesis mainly investigates the "islanded" mode of the marine microgrid, and the option of plugging it to the onshore utility grid is not studied. Overall, the microgrid in marine restructures the shipboard electric system and meets the increasing demands of improving marine energy efficiency and reducing fuel consumption.

Based on an overview of the recent studies and applications of microgrid for marine, there are significant amounts of investigations focusing on DC grid implementation. This is mainly because that the number of power components based on DC distribution, e.g. DC load consumptions, storage systems and some DG sources, is increased. DC-based microgrids can offer additional benefits of saving configuration space and simplifying grid design. DC microgrid systems are becoming more competitive and popular in the areas of data center security, renewable power generation & storage, vehicles and marine vessels.

2.2 Academic Research in Microgrid for Marine

Currently, in the study area of marine microgrid, to understand the reactions of shipboard microgrid system (SMS) operated under different load profiles is one of the most popular topics. These topics include power system analysis, fuel consumption estimation, novel power system evaluation and fault insertion combined with system restoration. In the following examples, modeling and simulation methodologies with respect to the topics aforementioned are presented.

2.2.1 Simulation Models of Shipboard Electric Power Systems

The electric propulsion solutions for marine nowadays vary depending on vessel types, available technologies and operation profiles. According to ABB vessel segments, offshore vessels, ice-going vessels, passenger vessels, cargo vessels, and special purpose vessels account for the majority of marine vessels.

Li Wang has established the simulation models for simulating the dynamic performance of a microgrid system feeding the electrical loads in a sailing boat [28]. The design of the shipboard microgrid system consists of a diesel generator, a wind turbine generator (WTG), two solid-oxide fuel cells (SOFC), a seawater aqua electrolyzer (AE), a battery energy storage system (BESS), a DC/AC inverter and an AC/DC converter (Fig. 16).

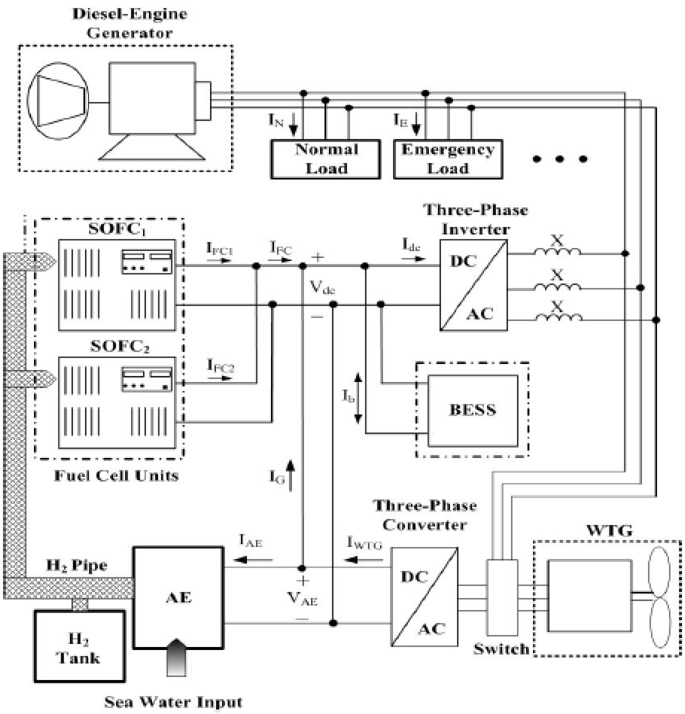


Figure 16: Configuration proposal of the microgrid system in a sailing boat-[28]

In this study of *Li Wang*, the general principle of the microgrid system and the relevant mathematical models are discussed. Based on time-domain steady state and dynamic simulations, the proposed microgrid system is validated in terms of stable supply of required power loads under both high load demand and low load demand conditions.

As shown in Fig. 16, the microgrid system includes four subsystems (in dashed boxes). The frequency of the loads can be maintained by those subsystems. Since the normal load can be interrupted while the emergency load needs to be constantly supplied, the diesel-engine generator should be started at proper times to compensate the lack of supply from the three-phase DC/AC inverter. The power flows on DC bus of this microgrid system is the combination of the output of AC/DC converter fed by WTG, the absorbed power of AE, the outputs of two SOFCs, the charge or discharge power of BESS, and absorbed power of DC/AC inverter. To conduct power system analysis, the mathematical models of some components in the microgrid system are presented below.

1) Battery Energy Storage System:

In this paper, the demand of power load and the power generation of the SOFC(s) determines the operation of the BESS during the simulation period. If $P_{FC}(t) > P_{Load}$, the BESS is under charging mode and the battery state of charge (SOC) at time t is expressed by:

$$\mathrm{SOC_{BESS}}(t) = \mathrm{SOC_{BESS}}(t-1) + (\mathrm{P_{FC}}(t) - \mathrm{P_{Load}}(t))\Delta t \eta_{ch} \tag{1}$$

The $SOC_{BESS}(t)$ and $SOC_{BESS}(t-1)$ are the capacities of the BESS at time t and t-1. η_{ch} is the charging efficiency. If$(P_{Load}(t) - P_{Diesel}(t)) \leq P_{FC}(t) < P_{Load}(t)$, the BESS is under charging and the battery capacity is given by:

$$\mathrm{SOC_{BESS}}(t) = \mathrm{SOC_{BESS}}(t-1) + (\mathrm{P_{FC}}(t) + \mathrm{P_{Diesel}}(t) - \mathrm{P_{Load}}(t))\Delta t \eta_{ch} \tag{2}$$

If $(P_{Load}(t) - P_{Diesel}(t)) > P_{FC}(t)$, the BESS is under discharging mode and starts to compensate the power shortfall. The battery capacity of the BESS is given by:

$$\mathrm{SOC_{BESS}}(t) = \mathrm{SOC_{BESS}}(t-1) + \frac{1}{\eta_{dis}}(\mathrm{P_{FC}}(t) + \mathrm{P_{Diesel}}(t) - \mathrm{P_{Load}}(t))\Delta t \tag{3}$$

Except the conditions mentioned above, the SOC of the BESS at any time should follow the constraints of $SOC_{BESS(\min)} \leq SOC_{BESS}(t) \leq SOC_{BESS(\max)}$. The upper and lower limits are the maximum and minimum allowable working window of the BESS respectively.

2) Solid-Oxide Fuel Cell:

The SOFC output voltage V_{dc} is expressed in terms of partial pressure of hydrogen, oxygen and water as:

$$\mathrm{V_{dc}} = \mathrm{NE_0} + \frac{\mathrm{NRT}}{2\mathrm{F}} \ln\left[\frac{\mathrm{PP_{H_2}PP_{O_2}^{0,5}}}{\mathrm{PP_{H_2O}}}\right] - \mathrm{r_{int}I_{FC}} \tag{4}$$

PP refers as the partial pressure, r_{int} is ohmic-loss resistance of SOFCs, F is the Faraday Constant, and E_0 is the reaction-free voltage of a cell.

3) DC/AC Inverter:

This power electronic unit manages the different dynamics of the SOFCs, BESS, WTG, and onboard load demands. The power line between inverter and load is approximated as purely inductive, and the inverter is assumed as lossless. Accordingly, the AC voltage and active power at the inverter output are given by:

$$P_{ac} = \frac{mV_{dc}V_L}{X}\sin\delta \tag{5}$$

The corresponding $P_{ac} = P_{dc} = V_{dc}I_{dc}$ and the molar flow of hydrogen is $q_{H_2} = \frac{N(I_{dc}+I_b)}{2FU}$, so the phase angle δ is calculated as:

$$\delta = \sin^{-1}\left\{\frac{\left[\left(\frac{2q_{H_2}FU}{N}\right) - I_b\right]X}{mV_L}\right\} \tag{6}$$

As a result, the output voltage of the inverter can be controlled by the modulation index m, and the output active power can be controlled by adjusting the hydrogen flow q_{H_2}.

4) Wind Turbine Generator System and Frequency Variation:

The WTG generates power of $P_{WG} = \frac{1}{2}\rho A_S C_P V_W^3$. The system frequency variation is expressed as $\Delta f = \frac{\Delta P_L}{K_{sys}}$. ΔP_L is the imbalance between power load demand and power generation, and K_{sys} is a system characteristic in terms of frequency.

Tiffany Jaster and *Andrew Rowe* model a hybrid electric propulsion system of a marine vessel in MATLAB Simulink with SimPowerSystems library [29]. In their work, the term "microgrid" is not used, but it provides methodology for the design of a shipboard "hybrid" power system and power management system. Because of that, the proposed system can also be regarded as a shipboard microgrid system to some extent.

The proposed hybrid propulsion system is beneficial within marine areas with strict environmental regulations. With the all-electric ship (AES) mode, the emission free target is achievable during low speed cruising or DP. The studied shipboard power system is modeled with the aim of evaluating the novel design and exploring the capability of the hybrid propulsion system. The target is to investigate the effectiveness of utilizing multiple energy sources.

The design of this hybrid system consists of three 215 kW marine diesel generators, a 150 kW fuel cell (FC), a 232 kWh ESS (three parallel Li-ion battery blocks), and two DC/AC inverters (Fig. 17). The hybrid generation system is connected to a 460 V AC bus. Ship propulsion system is configured with two 200 kW azimuth thrusters, and a 90 kW fixed pitch bow thruster supplementing DP operations.

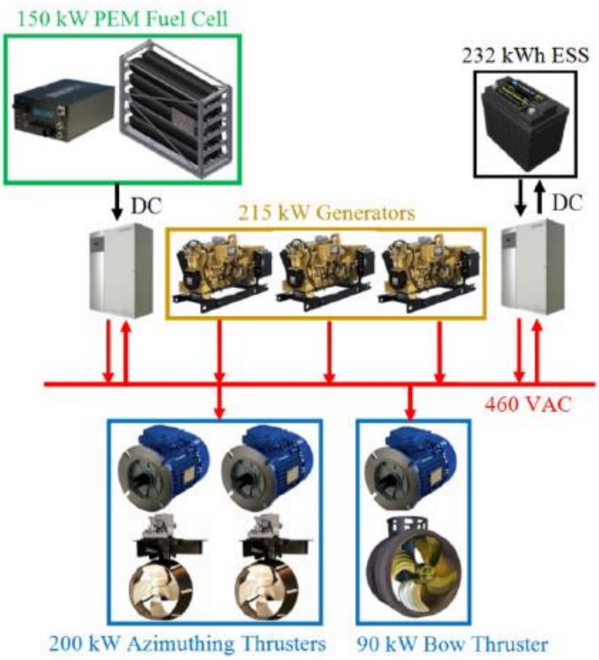


Figure 17: Configuration proposal of the hybrid propulsion system-[29]

In the study of *Bijan Zahedi* and *Lars E. Norum*, DC distribution system is implemented and a simulation platform of carrying out power sharing between the two diesels, a fuel cell module, and an ESS is developed in MATLAB/Simulink [30]. The choice of distribution voltage type (AC and/or DC) is of primary importance to the design of microgrids in electric vessels.

In order to pursue a system-level analysis of a shipboard DC distribution power system (Fig. 18), nonlinear properties of the power converters and interactions among the components should be analyzed for the system model.

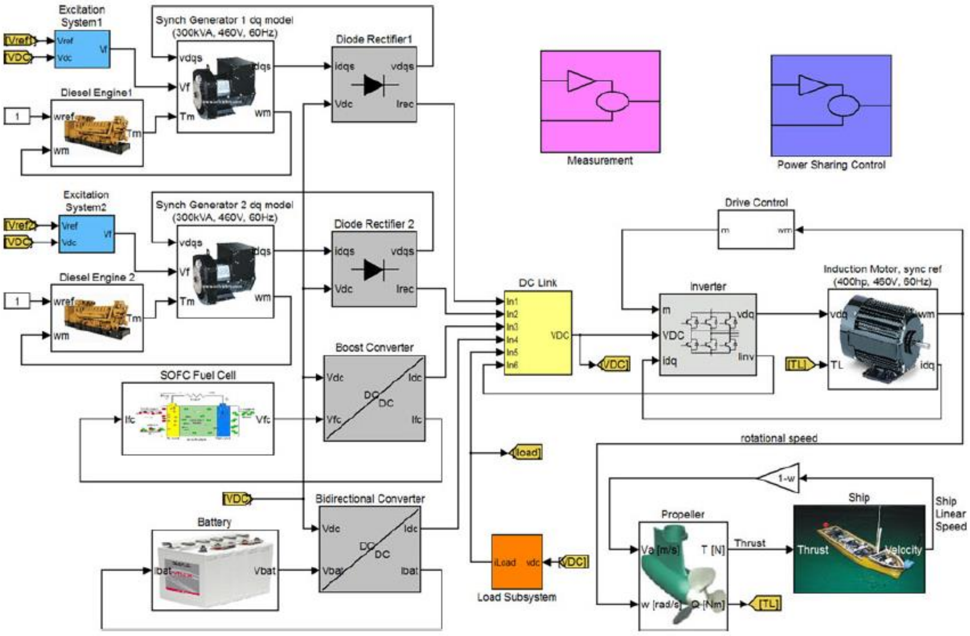


Figure 18: Configuration for system-level analysis of ship DC distribution power system-[30]

Prior to the system-level simulation, appropriate individual models in the system are achieved. Since the interfaces among connected models must be bidirectional and based on nonlinear averaging techniques, the study [30] emphases the use of nonlinear average value model for the bidirectional converters. In the simulated hybrid power system, the two synchronous diesel generators are rated at 300 kW each, the ESS is based on Li-ion battery, and the propulsion motor is a three-phase 460 $V_{L\text{-}L}$ induction motor (rated at 400 hp). Regarding the load profile, three sailing modes are proposed: 1) high speed 2) moderate speed 3) low speed. In addition, ship auxiliary and hotel load is rated at 125 kW and modeled by a constant impedance load.

DC currents of the different energy sources and loads (Fig. 19) represent their power contributions. According to the simulation results, with high vessel speed, the power load reaches the highest demand compared to those of the other two speed modes. Changing from the high speed mode to the moderate speed mode, the power load demand is reduced by 70%. During this time, the generator 2 is shut down leaving generator 1 and fuel cell to supply the power demand. In the mode of moderate speed, the ESS can be charged and discharged depending on the load level, and SOC is sustained by starting an idle diesel when it reaches the lower boundary, and shutting down an online generator when SOC hits its upper limit. Under low vessel speed, the power demand is mainly supplied by the fuel cell, and the generator 1 can be shut down if the ESS is not being charged. Through the entire simulation, the fuel cell is controlled on its rated value (20 A/s) so as to prevent from fuel starvation.

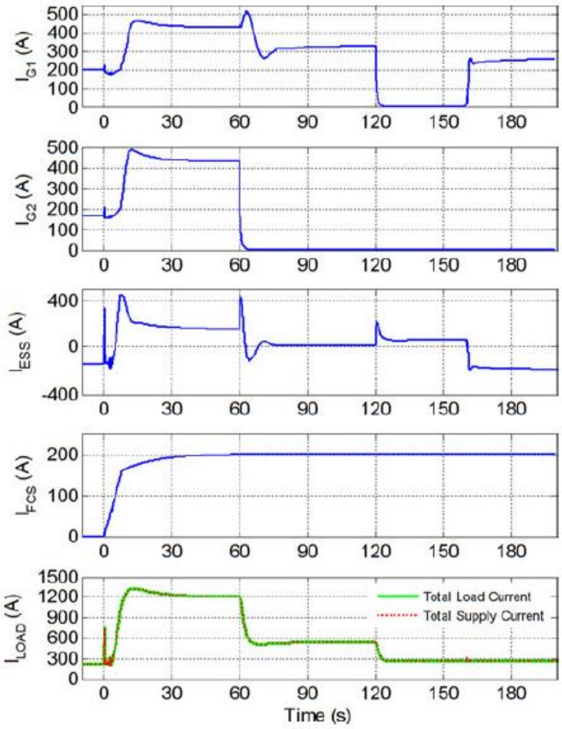


Figure 19: DC currents of the sources, ESS, fuel cell, and load-[30]

In this paper [30], the DC link voltage is regulated by using voltage droop control method [31]. More details about the control method for power sharing and DC voltage regulation in shipboard power distribution system is further discussed in section 2.2.2.

In short, *Bijan Zahedi* and *Lars E. Norum* establish a system-level simulation platform using the derived models for different components.

2.2.2 Voltage Regulation and Power Sharing Control in Shipboard DC Power System

Bijan Zahedi and *Lars Einar Norum* investigate voltage control and also power sharing between the generation sources in a shipboard DC power system [32].

Main DC sources in this system are fuel cells and ESS. The power system under study includes two diesel generators, one fuel cell module, and one energy storage system. The diesel engine, propellers and other mechanical components are also taken into consideration. Figure 20 illustrates the typical layout of a DC shipboard power system in a single line diagram. The “Clean Energy Source” element can be fuel cells and photovoltaics (PV) modules most probably. The “Energy Storage” can be based on battery or super capacitor.

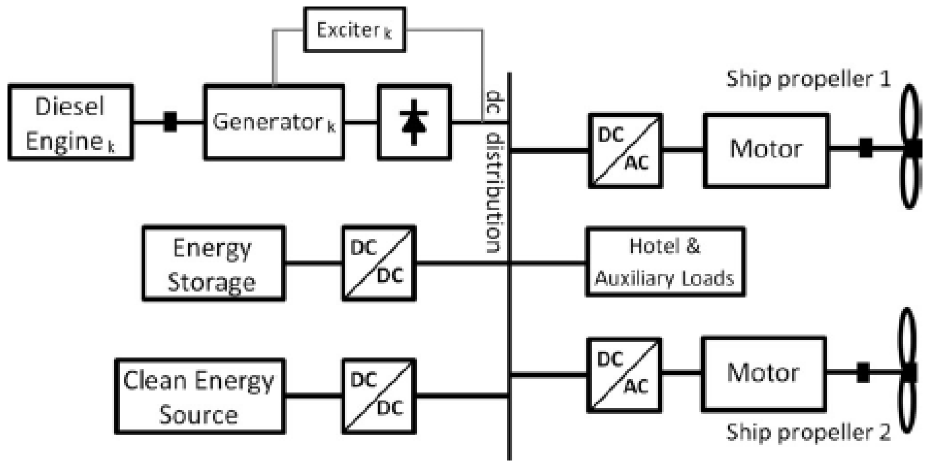


Figure 20: Typical layout of a DC shipboard power system in a single line diagram-[32]

The exact power sharing control cannot be finalized only through executing primary voltage droop. Thus, an advanced power sharing control is derived by implementing a higher level compensator to dispatch the load demand precisely according to the optimal loading range of a diesel engine. A compensation voltage is introduced by the compensator to adjust the DC voltage reference, so as to maintain the load sharing of the generator units within their optimal range. The described voltage regulator-exciter is depicted in Fig. 21. When the load demand increases, the compensator increases the voltage reference (v_{dc}^*) to deliver more power to the grid. As the load gets lower, the compensation voltage (v_{Comp}) reduces the power delivered from the generators.

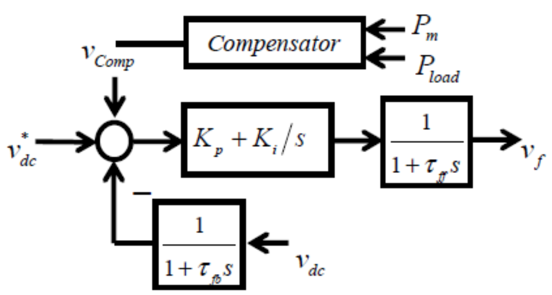


Figure 21: Block diagram of voltage regulator-exciter-[32]

2.2.3 Real Time Implementation of Microgrid Reconfiguration

Operating an islanded distribution power system requires a better consideration of uninterrupted power supply and an efficient reconfiguration when a fault happens. Reconfiguration is a control action which includes load or generation shedding and other measures to make the remaining loads unaffected under fault conditions. The work of *F. Shariatzadehand* and *R. Zamora* in 2011 uses genetic algorithm (GA) and graph theory based methodologies to reconfigure a shipboard microgrid in a real-time case study [33].

The proposed GA is used on an 8-bus shipboard power system to find out optimal configuration for meeting the predefined objectives and system constraints. The microgrid system is simplified by using graph representation, and then the corresponding matrix representation is established. Based on the matrix representation, optimal solutions for balancing the remained system after fault isolations can be found.

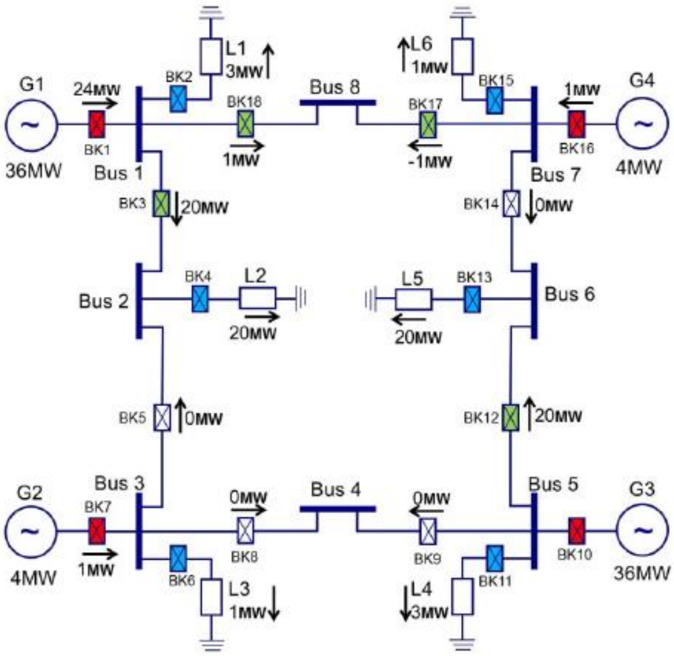


Figure 22: A shipboard microgrid system-[33]

Figure 22 depicts a shipboard microgrid system. It consists 6 switchboards (bus 1, 2, 3, 5, 6 and 7), two cables (bus 4 and 8), 4 generators (G1, 2, 3 and 4), and 18 breakers. Those components can be plotted by implementing graph representation in order to formulate the system mathematically by means of its matrix. Based on the established reconfiguration algorithm, a real-time implementation is carried out using real-time digital simulator (RTDS) and dSPCAE-DS1104 R&D controller board. RTDS simulates the shipboard microgrid system and sends fault signals to dSPCAE controller. If a fault is detected by the controller, dSPCAE will run the reconfiguration algorithm and send back the status of load breakers to RTDS for maintaining the unaffected loads.

In the real-time test, all load breakers are closed in normal operation condition, but after faults occur, e.g. on bus 1 and 5, only two load breakers remain closed. As the results shown in [33], GA reconfiguration algorithm performs nicely in real-time implementation for a SMS.

2.2.4 Optimal Sizing of a Shipboard Microgrid with PV and ESS

Hai Lan and *Shuli Wen* propose a method to determine the optimal size of a power generation system, which is integrated with diesel, PV and ESS in a stand-alone shipboard power network [34]. The optimal sizing minimizes the investment cost, fuel cost and the CO_2 emissions. In order to validate the concept, the authors implement the proposed method to optimize the costs and emissions for a hybrid PV/diesel/ESS system (Fig. 23). The project is involved in "Study on the Application of Photovoltaic Technology in the Oil Tanker Ship in China".

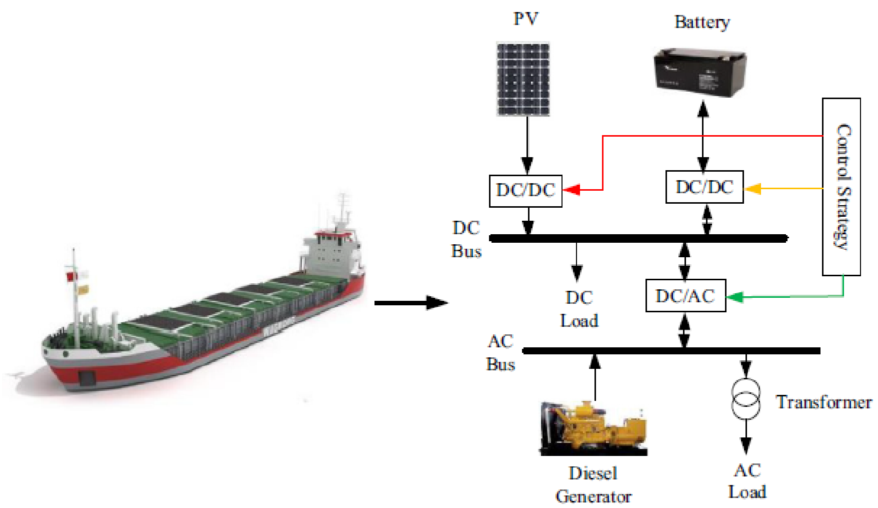


Figure 23: A shipboard microgrid system with PV and ESS-[34]

First of all, the study of *Hai Lan* and *Shuli Wen* focuses on modeling of a shipboard microgrid system. The microgrid system consists of a PV generation unit, a diesel generator supplying major power demand and an ESS storing energy surplus and improving the redundancy of the system. The tanker ship navigates from Dalian in China to Aden in Yemen. According to this navigation routine, the optimization includes 3840 hours in a year. The irradiation, temperature and the load profile are sampled every hour (Fig. 24). Variations of the power load under five operational conditions are modeled: regular cruising, full-speed sailing, docking, loading/unloading and anchoring [34]. It should be noticed that the impacts of motion fluctuations of the ship are not considered in the study.

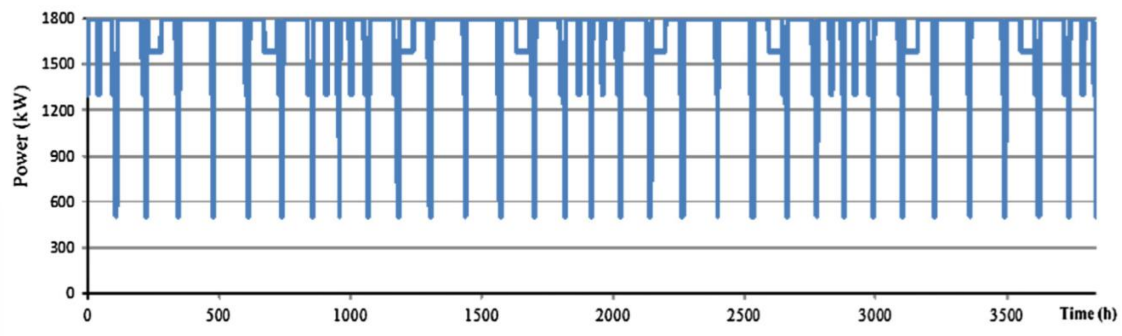


Figure 24: Hourly ship load profile along routine of interest-[34]

The models of the system components (PV unit, diesel generator, and battery) are derived mathematically. Relevant expressions for those models can be found in [34]. According to the mathematical models, operational constraints of the studied system are listed as following, where $P_{d\,(s,t)}$, $P_{PV\,(s,t)}$, $E_{ESS\,(s,t)}$ are referred to the outputs of the diesel generator, PV and ESS respectively at time t in season s.

$$P_{d\,min} \le P_{d(s,t)} \le P_{d\,max} \tag{7}$$

$$P_{PV(s,t)} \le P_{PV} \le P_{PV\,max} \tag{8}$$

$$E_{ESS(s,t)} \le E_{ESS} \le E_{ESS\,max} \tag{9}$$

$$P_{d(s,t)} + P_{ESS(s,t)} + P_{PV(s,t)} = P_{Load(s,t)} \tag{10}$$

Based on the two objectives of this study, a multi-objective problem is set up. The corresponding multi-objective functions are:

$$\mathrm{min}f_1 = \mathrm{Cost}_{fuel} + \mathrm{Cost}_{PV} \cdot \mathrm{CRF}_{PV} + \mathrm{Cost}_{ESS} \cdot \mathrm{CRF}_{ESS} \tag{11}$$

$$minf_2 = Emission_i = \sum_{s=1}^{4} \sum_{t=1}^{960} Em_{fuel} \cdot (a \cdot P_{d(s,t)} + b \cdot P_d^{rated}) \tag{12}$$

Where, the total cost calculated in “$minf_1$" consists of fuel cost, installation and replacement costs of PV and ESS. The capital recovery factor (CRF) is used for converting initial cost to an annual capital cost. The cost functions are represented in the form of net present cost:

$$Cost_{fuel} = \sum_{s=1}^{4} \sum_{t=1}^{960} Price_{fuel} \cdot (a \cdot P_{d(s,t)} + b \cdot P_{d}^{rated}) \tag{13}$$

$$Cost_{PV} = (C_{capital}^{PV} + C_{replacement}^{PV}) \cdot P_{PV} \tag{14}$$

$$Cost_{ESS} = (C_{capital}^{ESS} + C_{replacement}^{ESS}) \cdot E_{ESS} \tag{15}$$

After that, Multi-Objective Particle Swarm Optimization (MOPSO) is implemented to solve the multi-objective optimization problem. In the case of MOPSO optimal sizing (minimizing cost and emission), the total diesel output power is at minimum level with the application of PV and battery. Compared to the cases without optimal sizing or with other optimization techniques, the scenario with the proposed MOPSO methodology demonstrates that the selected size of the PV generation and the energy capacity of $LiFePO_4$ ESS make the hybrid system (Fig. 23) achieve the lowest net present cost and produce the minimal emission.

After reviewing the methodologies summarized in the literature review part, the system-level analyses for shipboard microgrids are well investigated. Most of the raised methodologies can be referred for developing the actual concepts in this thesis.

3 Microgrid Feasibility for Marine

First of all, in this chapter the problems and goals defined in this thesis are recapped. Some of the methodologies from the prior art studies discussed in Chapter 1 and 2 are not specified for the microgrid scope and system-level scale. In this chapter, in order to investigate the feasibility of establishing microgrids for marine vessels, crucial technologies related to energy storage system, vessel automation & control system and inland microgrid solutions are studied. Based on that, the possibility of implementing existing solutions for marine microgrids is investigated.

3.1 Problem Definition

In this thesis, a shipboard microgrid system (SMS) is set up with integration of energy storage and solar sources to the existing diesel generators within an islanded network. In order to investigate the feasibility of microgrid operation in marine vessels, a power management system (PMS) consisting of Load Sharing Strategy and Peak Shaving Strategy is formulated. Subsequently, time-domain simulations are carried out to validate the main concepts.

At first, some of the prior art, in terms of shipboard power network, electric propulsion, energy storage system, and power management system, from both industrial and academic studies are presented. Based on that, feasibility of microgrid solutions for marine vessels is investigated. After that, the actual design and control concepts are developed, and testing case scenarios are defined. In addition, time domain simulations are implemented to verify the proposed methodologies.

According to the prior art studies, DC based shipboard power system is more of interest. Some recommendations for analyzing the generic microgrid architectures and the specific applications are given by the "DC Microgrid Scoping Study" [35]. These recommendations provide valuable study guidance and reveal future potentials of marine microgrid studies.

In order to assess the system stability and validate the PMS when implementing this shipboard DC microgrid system with installation of ESS and renewable resources, this project facilitates a detailed MATLAB simulation-based system level study accounting for the factors of realistic load/generation profiles, stability and power quality of DC microgrids.

The overall target of this project is to achieve a highly energy efficient microgrid system for marine vessel, facilitate dynamic response to load fluctuations, and enhance existing vessel information and control system. Prior to the system-level simulation, models of the energy resources, energy storage, and power electronic converters need to be obtained. After that, control functions and stability of operating the proposed shipboard microgrid system (SMS) are verified.

3.2 ABB Storage and Control Systems

In order to improve performance and manage power flows of islanded electric power systems, control and storage subsystems are needed. Some of the ABB control and storage solutions are discussed below.

3.2.1 Storage Solutions

In a power grid, volatilities caused by renewable integration and loading profile fluctuation impact the grid stability. For marine vessels, persistent load fluctuations introduced by the rotating motion of the propeller and wave-induced motions, exist throughout the normal operations. The presence of renewable energy sources also increases volatility in shipboard power systems. Accordingly, energy storage system (ESS) embedded with specific control functions is increasingly recognized by the marine industry. Energy storage and control systems for marine can take advantages of the experience and techniques from the distributed microgrid systems in other areas.

ABB's Energy Storage Module (ESM) provides a packaged solution that stores energy produced by different sources. The energy is usually stored in batteries for specific energy demands. ABB ESM portfolio includes [36]:

- Community Energy Storage (CES) System: 25 kW – 100 kW / 30 min – 4 hours; 2 enclosures: Batteries and Battery Management System (BMS), and inverter & switchgear.

- Distributed Energy Storage (DES) System: 100 kW – 5 MW / 15 min – 4 hours; Containerized solution with batteries, BMS, inverter, inverter PLC, switchgear, and transformer.

- Grid connection equipment: 400 kVA – 20 MVA; one container with inverter, inverter PLC, switchgear, and transformer.

- Battery containers: containerized solution with batteries, racks, and management systems.

Battery Energy Storage System (BESS) is an ESM technology based on battery devices. BESS is a solution, which makes the power network smarter by raising power quality with better voltage and frequency regulation as well as component redundancy. Accordingly, the scheme of BESS can be applied in islanded DC microgrids for implementing load sharing, stabilizing DC link voltage and shaving load fluctuation.

Within the scope of BESS, EssPro™ Battery Energy Storage System offers a distributed solution for supporting the grid (Fig. 25). The battery type includes lithium-ion (Li-ion), sodium-sulfur (NaS), nickel-cadmium (NiCd), and lead-acid [37]. At the same time, The EssPro™ electrical plant and inverter controller (EPIC) enables manual and automatic operation of all BESS components in various control modes [37].

Application	EssPro Grid benefits
Frequency regulation	EssPro Grid absorbs and injects power in order to keep grid frequency within pre-set limits.
Spinning reserve	To provide effective spinning reserve, the EssPro Grid is at an adequate level of charge ensuring fast response to generation or transmission outages.
Capacity firming	EssPro Grid smoothes the output and controls the ramp rate of wind and solar power generation to mitigate rapid voltage and power fluctuations caused by their variable nature.
Peak shaving	EssPro Grid can be installed close to loads and shift expensive peak load to low tariff times.
Power quality	EssPro Grid eliminates short voltage sags – eg, caused by power system faults or the start-up of a large motor.
Uninterruptable power supply	In case of a mains failure or blackout, EssPro Grid can bridge the gap in supply.
Load leveling	EssPro Grid stores power during low-load periods and delivers it during periods of high demand in order to reduce the load on less economical peak-generating facilities.
Voltage support	To help maintain the grid voltage, EssPro Grid injects or absorbs both active and reactive power.

Figure 25: EssPro™ energy storage applications-[37]

3.2.2 Control Solutions

In presence of distributed generation and load, control devices are needed to interconnect the components in the system, so as to execute system-level operations and communications. For the battery technologies, it is a common practice to use a bidirectional converter to incorporate energy storage in electric power system and provide battery control. In order to maintain the acceptable voltage level, system redundancy and power quality in DC microgrids, the active power balance in the system needs to be controlled.

EssPro™ Power Conversion System (PCS) is usually used for energy storage applications. It acts as an interface between the grid and the batteries [38]. It allows energy to be stored or accessed whenever it is needed. For microgrid application, the PCS supplies critical loads in any circumstance by producing controlled local generation.

UNITROL® automatic voltage regulators (AVR) and static excitation systems (SES) offer solutions for any type and size of power plant [39]. Because of its high flexibility, it enables voltage regulation for various types of applications. For instance, power plants with diesel engines, electrical propulsion for marine, and diesel electric locomotives can all implement UNITROL® control concept. Due to its design features and built-in control functions, it becomes a compact and robust regulator for both AC and DC voltage inputs. Moreover, it obtains an Ethernet-based fieldbus interface, which makes it highly probable to be connected to a larger scale communication network [39].

3.2.3 Marine Vessel Information and Control – System 800xA

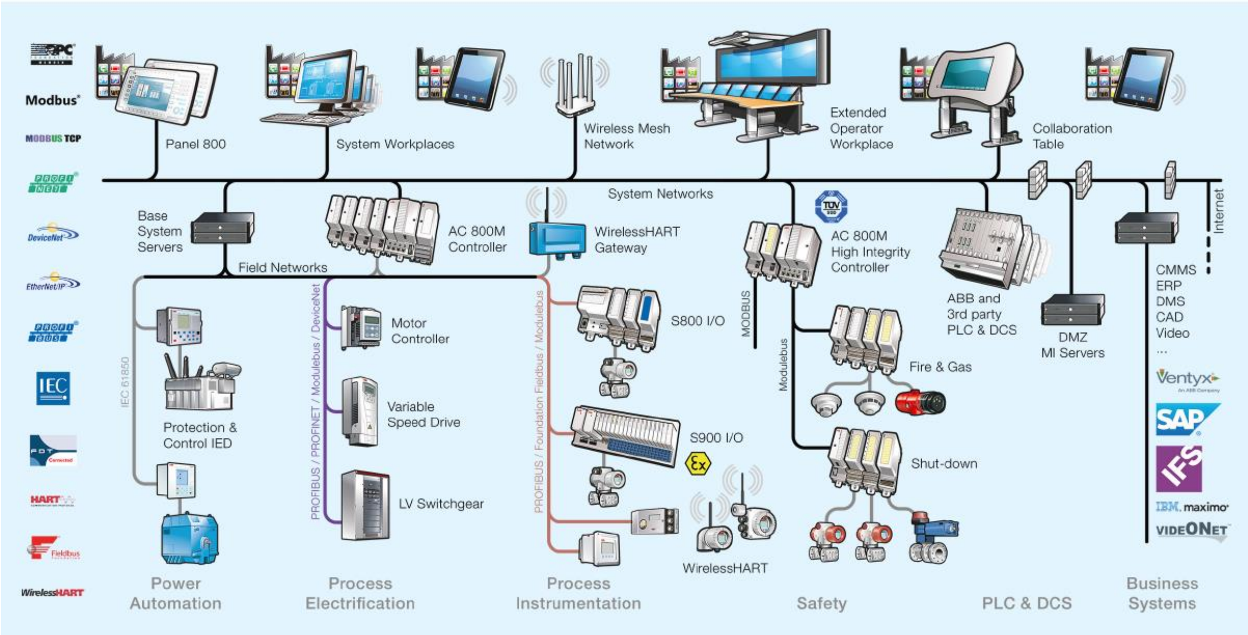


Figure 26: ABB Marine automation and control system - 800xA-[40]

System 800xA is an extended marine automation system offering services beyond traditional automation system [40]. It is an automation platform designed for users with excellent connectivity capabilities. Because of that, this integration system builds up a network where plenty of applications, plant systems, and devices are connected. All information is available for optimizing normal operations, control performance and protection under faults. Figure 26 shows the system diagram of ABB 800xA.

Advisory Systems: performance management of the vessels	Power Energy Management System (PEMS)	Third Party DCS Access
• EMMA® Advisory Suite: Minimize energy consumption • OCTOPUS® Advisory Suite: Maximize availability and safety	• An advanced **control concept** prepared for new and alternative energy sources • Used on DINA Star	• AC 800M control and I/O products • Modbus interface • Extend the functionality

Table 2: Functions and benefits of utilizing System 800xA

Table 2 summarizes some useful functions and benefits of utilizing System 800xA. To emphasize, 800xA provides connectivity to distribution control systems (DCS), as well as third party devices and applications.

3.3 ABB Microgrid Solutions - Microgrid Plus System and PowerStore

Land-based microgrid technologies are more investigated and industrialized than those of marine microgrid. This section presents the ABB solutions for land-based microgrids, so as to investigate if microgrids for marine vessels can lean on some of the concepts raised from inland microgrids. The investigation is carried out from aspects of grid control strategies and system-level storage solutions.

ABB’s microgrid offer energy storage solutions as well as automation and intelligent control solutions that can manage renewable energy integration in remote or islanded grids, ensuring outstanding power quality and grid stability [41].

ABB's microgrid solution consists of Microgrid Plus System™ and PowerStore™ flywheel or battery-based grid stabilizing system [41]. They build up land-based microgrids with system-level control functions and energy storage solutions. Normally, ESS is embedded to the microgrids and work synergistically with control functions. In this way, grid stability and redundancy are maintained. Figure 27 gives an overview of the ABB microgrid solutions.

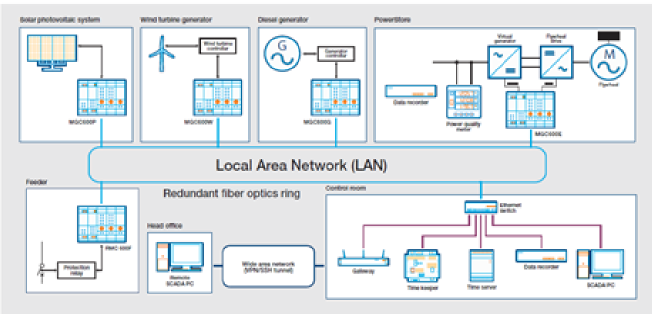
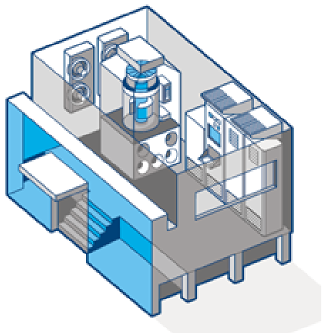
Microgrid Plus System	PowerStore
Specially designed networked control system responsible for coordinating the operation of hybrid power stations	Grid stabilizing system that offers real and reactive power to enable intermittent renewable energy to be integrated into grids
	
•Maximizes fuel savings •Optimizes use ofrenewable energy •Guarantees optimum loading and spinning reserve in fossil fuel generators •Distributed logic enhances reliability and scalability for future system expansions	•Can be used in isolated grids or in grid support mode •Maximizes fuel savings through highest possible renewable penetration •Ensures high power quality by stabilizing renewable energy generation

Figure 27: Overview of ABB’s microgrid solution-[41]

3.3.1 Microgrid Plus System

ABB Microgrid Plus System™ is a distributed control system for microgrid [41]. It is a specially designed network control system. It is a technology responsible for coordinating the operations of hybrid power plants and integrating renewables into microgrids [42]. Table 3 lists most of the functions of the ABB Microgrid Plus System.

Function	Definition
Renewable Energy Integration	Ensure sufficient capacity is available in microgrid for renewable energy integration
Storage / Stabilizing Integration	Designate available assets for smoothing. As well as synchronizing sources
Archiving	Log important and significant events and occurrences
Managed load demand	Monitoring and managing connected loads
Generator scheduling/ dispatch/ start-stop	Maintain generator status and operation commands
Generator Power Sharing (Active & Reactive Power)	Set active & reactive power set points for supplying loads
Generator configuration management	Configure generator settings and parameters
Generator overload capability	Calculate the overload capability and set value in generator
Feeder proactive load shedding and automatic microgrid black start;	Managing feeder automation parameters for shedding and reconnection.
Control of voltage, frequency in standalone/isolated grids	Maintain desired operating parameters
Solar PV generator power limitation set point	Power generation in solar PV can be limited
Determine and manage the energy storage system state of charge	Monitoring capacity and managing the energy storage systems within the microgrid

Table 3: Functions of the Microgrid Plus system

The unit manages the energy flow within a power network to ensure sufficient power reserve, voltage stability, and balance between supply and demand in the power grid. It also optimizes the use of intermittent energy sources. The Microgrid Plus System can be implemented for different setups. Figure 28 presents a typical example of land-based isolated PV/diesel microgrid.

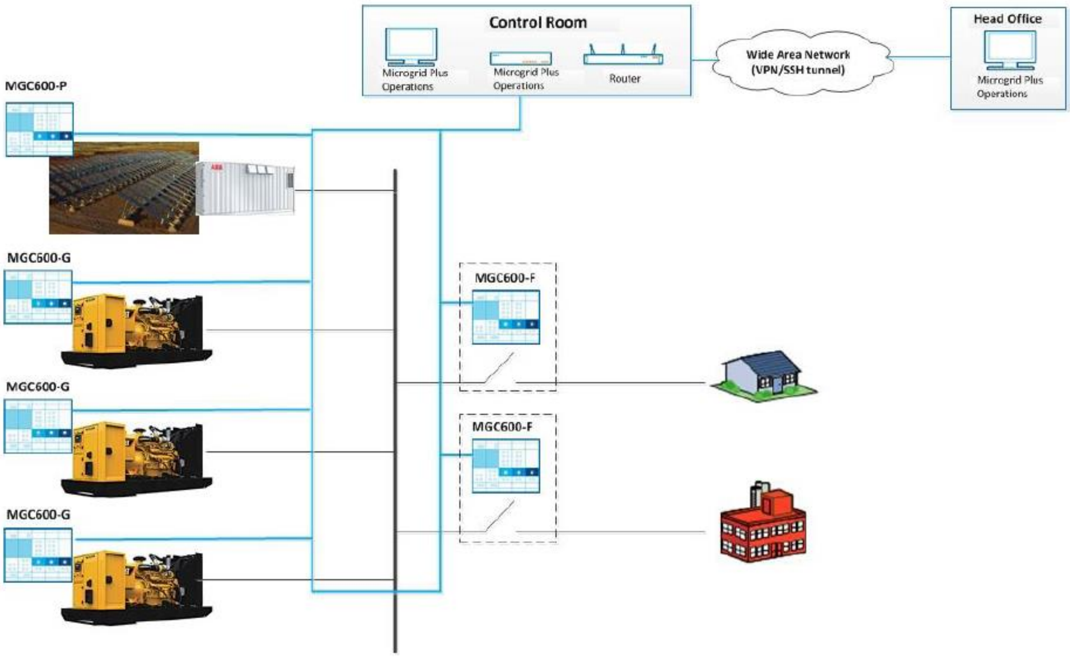


Figure 28: Typical schematic of isolated PV/diesel microgrid-[42]

In the microgrid plus system, MGC600 microgrid controller package (Table 4) is used to manage and automate distributed power generation systems [43]. It contains various controllers with different functions to allow communication between the microgrid devices. MGC600 controllers are deployed into the microgrid system in order to allow system-level communication. Different electrical devices select different types of firmware.

Firmware / Controller	Description
Diesel/Gas generator (MGC600G)	To control, monitor and interface to diesel generators
Distribution Feeder (MGC600F)	To control, monitor and interface to feeders and their protection relays
Photovoltaic Solar (MGC600P)	To control, monitor and interface to solar array inverters
Single/Multiple Load (MGC600L)	To control, monitor and interface to large loads like crushers, boilers, etc.
Hydro generator (MGC600H)	To control, monitor and interface to hydro plants
Energy Storage System (MGC600E)	To control, monitor and interface to the ABB PowerStore or other energy storage devices
Network connection of Microgrid (MGC600N)	To control, monitor and interface to other microgrids or larger grids
Wind Turbine (MGC600W)	To control, monitor and interface to wind turbines

Table 4: MGC600 microgrid controller firmware-[43]

3.3.2 PowerStore

PowerStore™ provides microgrids with comprehensive energy storage solutions [41]. It works via controlling the power outputs of generation resources and energy storage system in a coordinated manner. It supplies the grid power demands with excellent stability and reliability. PowerStore™ facilitates intermittent renewable energy to be integrated into the grid, and it offers active power support to compensate load volatility.

In addition, it can be implemented in industrial and commercial areas where fuel saving and power production scheduling are critical. Table 5 summarizes the functions of PowerStore storage devices.

Functions of PowerStore storage device	
Scheduling	Frequency Droop Control
Operation Modes	Voltage Droop Control
Peak Shaving	Power Factor Correction
Step Load Capacity	Battery lifetime optimization
Spinning Reserve Capacity	Automatic Recharge

Table 5: Functions of PowerStore storage devices

To some extent, PowerStore is a flywheel or battery based grid stabilizer. It consists of flywheel energy storage or batteries energy storage, power converter system, and operator interface [41].

In the PowerStore converter system, multiple converter pairs are paralleled to achieve the desired model rating. Additionally, an operator interface is used to monitor the storage device and converter components and to provide access to historical data. The PowerStore can be configured in three different sizes: 500, 1000 and 1500 kW [41].

3.3.3 ABB Microgrid - Real World Examples

A project named Marble Bar (Horizon Power), a PV/diesel hybrid power station, implements ABB solution of PV/diesel microgrid with PowerStore grid-stabilizing technology and Microgrid Plus System [44]. Scheme of this project is shown in Fig. 29. The resulting system consists of four diesel generator sets (rated at 320 kW each), one PV unit with a capacity of 300 kW, a PowerStore-flywheel with 500 kW capacity, and a Microgrid Plus System. The project has 405000 liters of fuel saved annually and 1100 tons of CO_2 reduction annually. It improves reliability and stability of power supply, and also achieves 60% of the daytime electricity demand supplied by the PV unit.

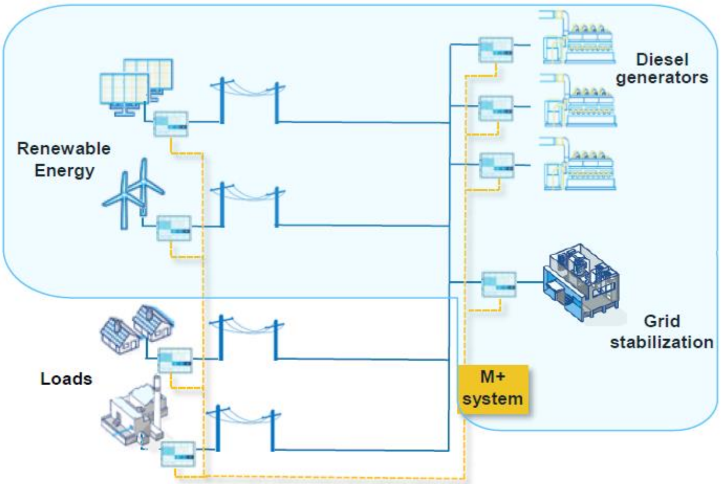


Figure 29: Schematic of PV/diesel hybrid power system; Source-[44]

Laing O‘Rourke construction camp, the world first large-scale portable solar integrated plant, is established by ABB microgrid solution integrating a solar PV unit (141 kW) into diesel generation sets (4 × 450 kW) via the Microgrid Plus System [44]. Laing O‘Rourke obtains annual diesel fuel saving of approximate 88865 liters, and this portable integrated power system is extendable with energy storage system.

The PowerStore-battery solution used for Legion House (Grocon, KLM group), stabilizes the islanded power network against fluctuations in frequency and voltage [44]. The building operates without any connection to the grid. This ABB microgrid system enables 100% renewable operation with biogas derived from renewable sources.

3.4 Feasibility of ABB Microgrid Solutions for Marines

Energy storage and control solutions for microgrid operation in marine vessel build a foundation of a stable, reliable, smart, and efficient shipboard power network. As shown in previous studies, ABB has a strong performance in supplying ESS and control system for land-based microgrid. Also, ABB Marine has a product portfolio delivering vessel information and control platform. ABB microgrid projects of land-based PV/diesel hybrid power systems are already developed and set feasible prototype for applications in marine vessels. At the same time, shipboard advisory systems and power energy management systems are being facilitated by ABB.

According to the prior studies, there are two possible control strategies for regulating and stabilizing shipboard power systems: Load Sharing/Voltage Droop Control and Peak Shaving based on high-power ESS technology. These strategies are used to implement DC network voltage regulations and stabilize the shipboard microgrid under load fluctuations. Meanwhile, the energy reserved by ESS improves the redundancy of the network, which further leads to an enhancement in system reliability. After that, this section investigates on the feasibility of applying and innovating existing ABB microgrid solutions for marine vessels.

From ESS point of view, EssPro™ Battery Energy Storage System and PowerStore are able to provide power capacity of min. 100 kW up to 30 MW (each unit), and energy capacity of min. 200 kWh up to 7.2 MWh (each unit). The battery DC voltage range is up to 1.2 kV [37]. Accordingly, together with battery management system, the existing energy storage systems ensure modular design and flexible capacity sizing. The energy storage device is able to regulate the power flow by charging/discharging power to the grid when energy output varies according to the load fluctuations, or during extreme weather and motion conditions. These conditions match the scenarios of shipboard microgrid operations.

From the control solution point of view, as discussed in subchapter 3.2, UNITROL® AVR and static excitation systems are flexible to be used for any type of power generation unit. It can be customized according to different engineering requirements. One of the application examples of UNITROL® 1000 is for marine electrical propulsion and auxiliary supply [39].

Regarding to the system-level control solution, ABB Marine automation and communication system, 800xA, can serve as a platform with third party access ports. This fundamental platform is to be integrated with ABB Microgrid Plus System, so as to expand the existing service portfolio and enhance vessel information and control system. Therefore, the inland microgrid firmware and control functions are utilized in marine microgrid, and a new concept, Mplus_800xA (Fig. 30), is defined for the shipboard microgrid system (SMS). It must be noted that this is purely a conceptual study and the performance, operations etc. are not related to the actual ABB products.

Table 6 in Appendix A summarizes some of the results obtained in this feasibility analysis. This chapter mainly presents qualitative analysis of existing ABB land-based microgrid solutions, relevant functions and availability of modification for marine applications. More detailed research methodologies about system configurations, actual control strategies and test scenarios are pursued in Chapter 4.

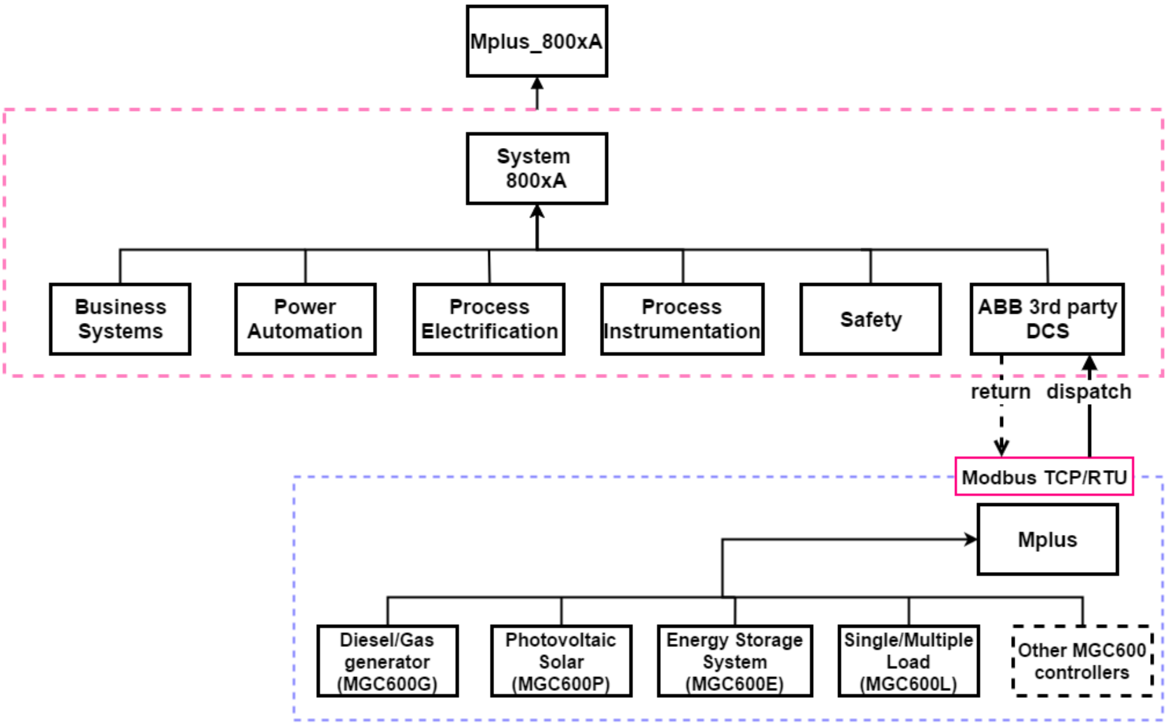


Figure 30: Mplus_800xA schematic diagram

4 Proposed Methodology

In this chapter, the proposed methodology for operating and controlling the marine microgrid is presented. The actual technical solutions are determined to configure the shipboard microgrid and develop the control functions. Then, validation of the operation stability under different scenarios is conducted. Accordingly, power management strategies for marine microgrids with renewables, ESS and diesels are formulated.

The design of the shipboard microgrid for marine vessels begins with the acquisition of system configuration. The arrangements of switching devices and buses need to be discussed. Considering the factors of operation reliability, cost and deployment area, four types of arrangements are studied.

Moreover, the vessel's main specifications, e.g. the dimensions, speed level and machinery data have been given by ABB's delivery to Dina Star. At the same time, the operation data of an Offshore Support Vessel (OSV) with a number of operational modes are analyzed. These data are obtained from the experiences of ABB Marine [48] in order to determine the capacity size of ESS and define the simulation test scenarios in Chapter 5.

According to the characteristic of the load profile, specific power management strategies are developed. A peak shaving strategy is formulated for operations with Dynamic Positioning (DP), while a load sharing strategy is used for operations with transiting or non-dynamic positioning.

In the end, with respect to the battery state of charge (SOC), instantaneous power load demand and the specified loading range for the online diesel generators, the working flow of the generation system is presented. Using this working flow, time domain simulations are conducted in MATLAB Simulink, so as to demonstrate that the proposed shipboard microgrid system (SMS) can stably operate with proper power management strategies under various operating conditions.

4.1 System Configuration

Shipboard DC grid architecture obtains more compact structure compared to AC grid. Because of that, the DC grid configurations meet the size and weight demand restricted by the cabin structure of the vessel or offshore platform. The DC solid-state circuit breaker combined with isolating mechanical switch costs more than AC circuit breaker system [3]. Hence, an alternative approach to solve the raised problem should be proposed: onboard DC grid is configured by a combination of fuses, isolating switches and controlled turn-on/off power electronic devices [8].

Initially, the arrangement of a single bus with sectionalizing disconnectors is presented. The cost of this configuration is very low and the deployment area needed for it is minimal. ABB prototype of shipboard DC electric propulsion system, Dina Star Onboard DC Grid, implements this configuration with diesel generators supplying the electric power demands. Similarly, for the SMS proposed in this thesis, a single bus bar with two sectionalizing isolate switches in series is applied due to its lowest cost and simplest layout. Two disconnectors in series for sectionalizing are needed to ensure maintenance of any of the two sections without taking the full network out of service [45]. Furthermore, the use of the sectionalizing disconnectors improves the reliability and flexibility of the network, so that the system can expect the worst fault case of losing only half of the generation supply.

Figure 31 shows the layout of the single bus network. The four diesel generators are equally deployed on two sides of the tie switches. The total battery capacity is fairly split into two parts, namely two sub ESSs with the same battery settings are located at each side. When it comes to the PV array, the same solution as for the ESS is executed. With open sectionalizers, the DC distribution grid is divided into two sections and only parts of the network need to be de-energized for maintenance or in case of a fault. It should be noted that in Fig. 31 the MGC600 controllers are not nested into the layout, but later in subchapter 4.3, a design for system-level communication with MGC600 deployed is presented.

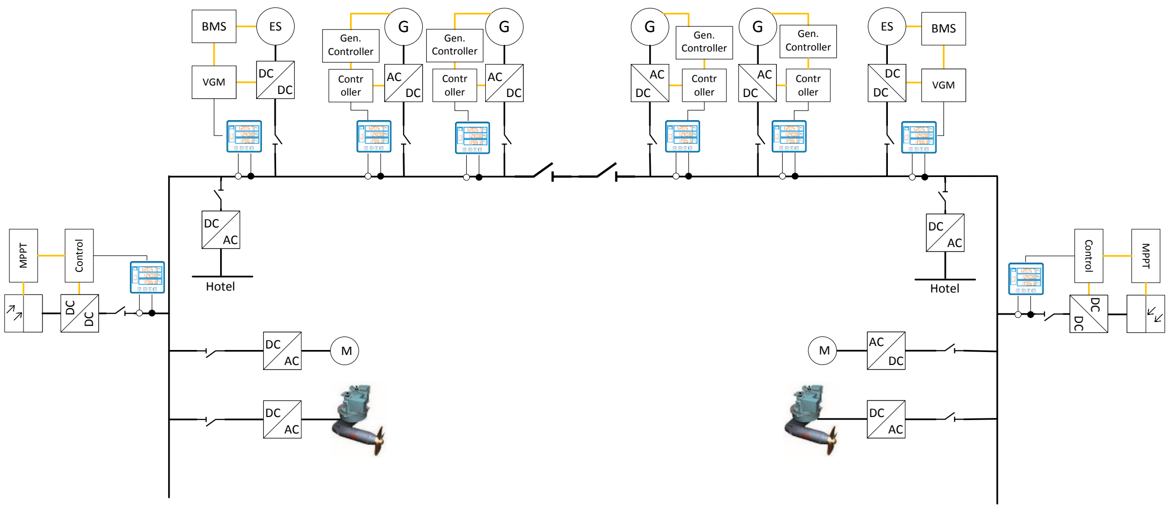


Figure 31: Single bus with sectionalizing disconnectors

Secondly, arrangement of double bus-double isolating switch is investigated (Fig. 32). With two switches and two buses for each circuit, flexibility of maintenance and reliability of relay protection are increased [45]. However, the number of the devices is increased and 28 DC isolating switches are utilized, so higher cost and greater areas are required.

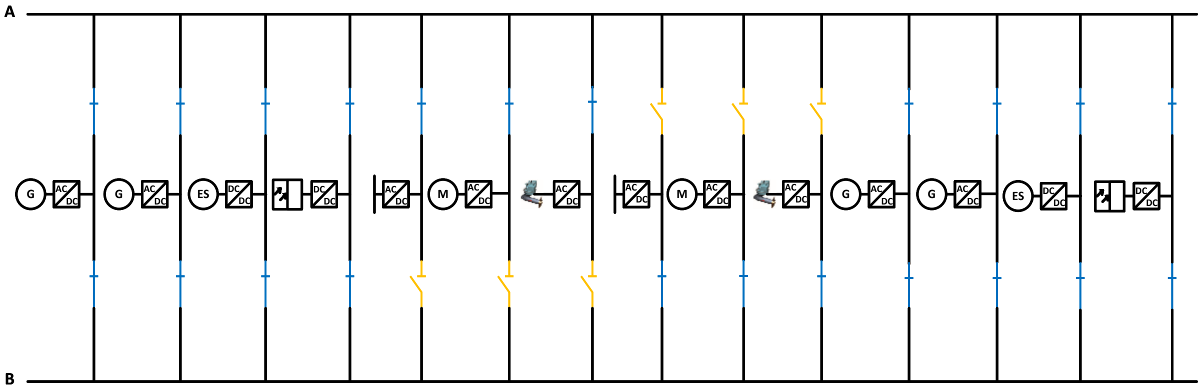


Figure 32: Double bus-double isolating switch

The configurations of one-and-a-half isolating switch and ring bus are also studied (Fig. 33, 34). In the one-and-a-half isolating switch, three isolating switches are lined up with two buses. Thus, one-and-a-half switches per circuit. This scheme provides good reliability that a single circuit failure does not interrupt any other circuits and a bus section fault does not affect any circuit loads [45]. Although as a DC grid configuration, the land area required by this "one-and-a-half isolating switch" is reduced than that in AC case, the complexity of the one-and-a-half isolating switch design and significant area demand for clearances makes it inflexible for an OSV.

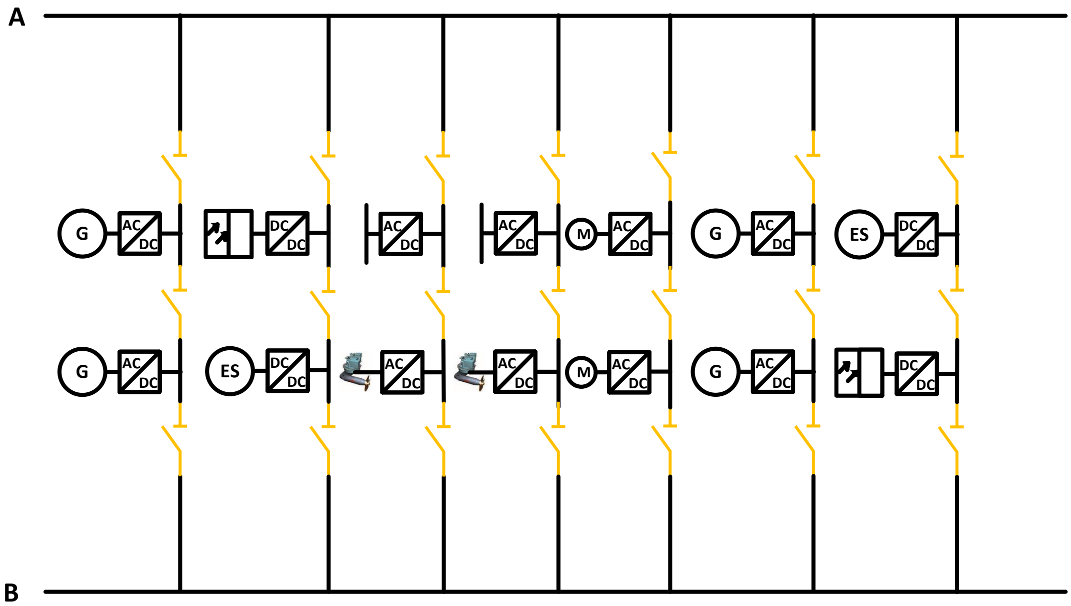


Figure 33: One-and-a-half isolating switch

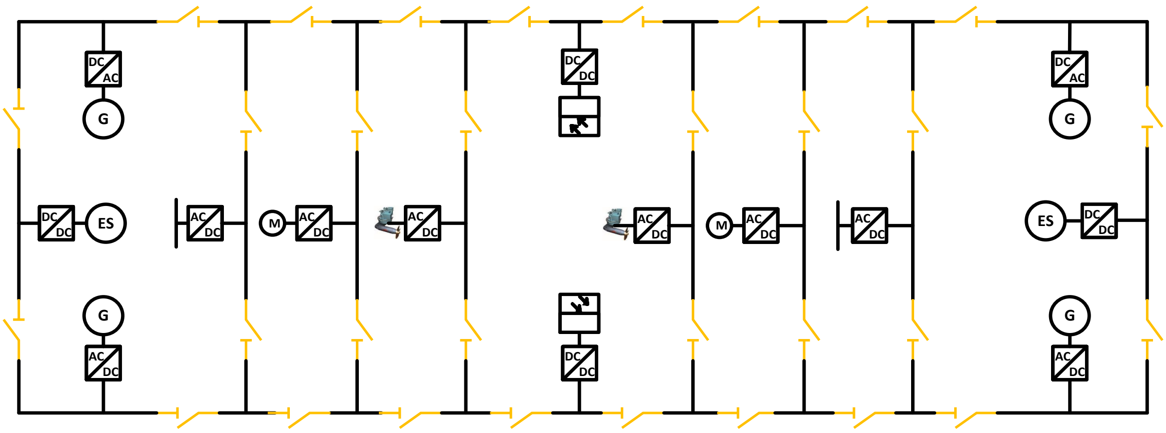


Figure 34: Ring Bus

About the ring bus arrangement, all isolating switches are in a ring with circuits connected in between. With respect to the reliability, this arrangement meets the security requirements by implementing specific fault solutions [8]. One circuit or bus section can be isolated without impacting the loads on another circuit. Since a lot more switching devices are needed for ring bus configuration, the cost of this scheme can be even higher than that of the double bus-double isolating switch scheme.

In conclusion, the single bus with sectionalizing disconnectors is selected due to its reduced cost, simplicity for expansion and minimal area demand. Table 7 compares the advantages and shortfalls of the configurations discussed above.

Configuration	Operation	Cost	Available Area	Complementary
Single Bus (with sectionalizing breaker)	Reliability can be increased by adding sectionalizing disconnectors	Least cost; fewer components	Least area: fewer components	**16** Isolating Switches used
Double Bus-Double Isolating Switch	Single circuit or bus fault isolates only that component	High cost; duplicated devices and more materials	Greater area: more devices and materials	**28** Isolating Switches used; Each group is fed from either bus
One-and-a-Half Isolating Switch	Bus fault will not affect any circuits, circuit faults isolates only that circuit	Moderate cost; cost is reasonable based on improved reliability and operational flexibility	Greater area: more components	**21** Isolating Switches used; Each circuit is fed from both the buses
Ring Bus	Single circuit or bus section fault is isolated	Moderate cost; additional components and materials	Moderate area: compact but hard to be extended	**32** Isolating Switches used; It is unsuitable for developing system

Table 7: Comparison of DC shipboard microgrid configurations

4.2 Operation Load Profile and Sizing of ESS & PV

In this subchapter, the sizing of energy storage and PV for a marine microgrid is discussed considering various load profiles.

Before analyzing the operation load profile, vessel specifications need to be clarified. In Chapter 1, marine vessel segments are discussed, and Offshore Support Vessel is selected to be the study subject in this thesis. Dina Star represents the ABB shipboard DC grid technology, so the vessel specification is determined based on the data published by Reach Subsea, who is the main contractual operator of Dina Star. Table 8 presents the machinery data, dimensions and speed level of the vessel under investigation. It shows the nominal mechanical powers of the diesel engines. Regarding to the operational efficiency, the diesel engines are suggested to work over an optimal range of 60% to 100% of the nominal power. [46]. For the generators, the minimum and maximum loading for each of the generators is 30% to 90% of the rated power [29].

Machinery	Parameters
Main Engines	4 x CAT 3516-2350kW, 1200-1800rpm; 1 x CAT C32-969 kW
Generators	4 x ABB 2350 kW, 1000 VDC distribution; 1 x ABB 969kW Harbor
Bow Thrusters	2 x Tunnel 925 kW-CPP; 1 x Azimuth redundant 880 kW-FP
Azimuth Propellers	Azipull 120, 2x2200 Kw-FP
Dimensions	**Parameters**
Length Overall (LOA)	93.80 m
Breath (moulded)	20.00 m
Depth (to shelter deck)	10.85 m
Depth (to main deck)	8.00 m
Draft (max)	6.5 m
Deadweight	Abt. 4900 t
Speed	**Parameters**
Max speed	15.1 knots
Econ speed	11 knots

Table 8: Dina Star specifications-[47]

4.2.1 Operation Load Profile

As mentioned before, according to the experiences of ABB Marine, the operation data of an OSV with a number of operational modes are analyzed. Table 9 gives a summary of the OSV load profile containing average power demand, load fluctuation and initial number of online diesel generators (before ESS and PV integrated) [48]. The duration percentage for each operating mode during 24 hours is shown in Fig 35.

Operation Mode	Average Power Demand (kW)	Load Fluctuation (kW)	# of Online Generators
Low dynamic positioning (LDP)	2352.9	1426.0	2
High dynamic positioning (HDP)	3778.9	1426.0	3
Anchor handling (AH)	3565.0	142.6	3
Harbor (H)	1212.1	71.3	1
Bollard pull (BP)	4705.8	142.6	4
Transit towing (TT)	5133.6	71.3	4
Transit supply (TS)	2388.6	71.3	2

Table 9: OSV operating modes and load profile

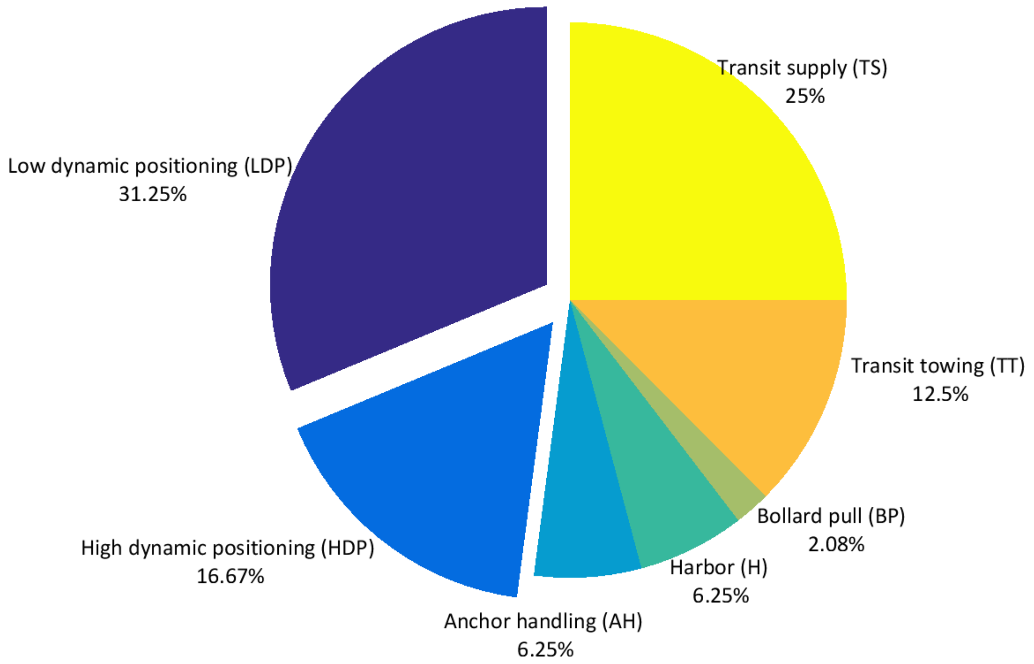


Figure 35: Seven operating modes of OSV and duration percentage for each within 24 hours

- **Dynamic Positioning:** Dynamic Positioning (DP) mode is used to keep vessel's position, and sustain safe performance and operation [4]. Depending on the value of average power demand, the DP mode is regarded as low DP (LDP) or high DP (HDP) (Fig. 35)

- **Anchor Handling:** Anchor Handling (AH) is one of the important operating functions of OSVs. Anchors for oil rigs are handled, and they are towed and anchored up. The average propulsion power needed for this mode is nearly the same as for HDP, but the load fluctuation in this mode is much lower than that in HDP mode

- **Harbor:** Harbor (H) operation usually requires power used for other electric equipment such as pumps, cranes, light, and heating. Since the power demand in this case is relatively low, harbor generator can be taken online while the other diesel generators are offline

- **Bollard Pull:** Bollard Pull (BP) is an operation for measuring the vessels towing capability. Thus, this mode demands high propulsion power. On the other hand, the load fluctuation under this operation is not significant

- **Transit Towing:** Transit Towing (TT) is an operation that the vessel is towing anchors, fleets or other offshore equipment. This therefore also requires high propulsion power. However, the load fluctuation is even lower than that of BP mode

- **Transit Supply:** Transit supply (TS) is an operation for transporting equipment on the sea. It usually runs with moderate or low propulsion power demand

4.2.2 Sizing of ESS and PV

Considering the load profile shown in table 9, the diesel generators and PV are dimensioned to yield the average power demands. On the other hand, the battery ramp rate should be dimensioned to meet the highest power fluctuation among all the operating modes. Therefore, the battery rated power, for this case, is set to be 1430 kW, which is sufficient to supply or absorb the load peaks when other generation units supply the average power demands.

The ESS consists of a battery bank and a bidirectional converter. The battery bank composes of Li-ion battery cells connected in series and parallel, so as to supply or absorb power peak of 1430 kW. As discussed in subchapter 4.1, the total battery capacity is equally split into two parts, namely two sub-ESSs with the same battery settings are located on each side. Accordingly, the battery power capacity, energy and current data are divided by two and applied for two sub-battery banks in the MATLAB simulation process.

Table 10 provides parameters for one battery module produced by Corvus Energy and also the data of the battery bank utilized in the proposed SMS [49]. Corvus Energy implements the customer's load profile and requirements to produce the only purpose-designed industrial lithium-ion battery system. The battery bank consists of Corvus AT6700-100 modules connected in series and in parallel in order to provide the investigated peak power demands under safe operating. In terms of the dynamic accuracy of battery behavior, the Li-ion ESS should be working within its operational capacity window, which is defined between 20% ~ 100% SOC [50].

AT6700-100 Module					Discharge		Charge	
# in series	# in parallel	Capacity (Ah)	Energy (kWh)	Voltage min-max (VDC)	Rated current (A)	Continuous current (A)	Rated current (A)	Continuous current (A)
1	1	75	7.5	76.8-100.8	750	450	375	225
5	8	3000	300	385-505	6000	3600	3000	1800

Table 10: Specifications of battery bank-[49]

The proposed SMS encompasses a PV system, which is divided into two subsystems due to the designed DC grid configuration. Table 11 presents the PV data that are used in this thesis. Based on the OSV size specified in table 8, the PV system is set to carry a PV capacity of 240 kW.

1 Module		
Nominal Power (Wp)	Area (m^2)	Efficiency (%)
250	1.6	15
Life time (yr)	Temperature range (°C)	Maximum voltage (V)
25	-40 to +85	1000

Table 11: Specifications of PV-[51]

4.3 Power Management System

According to the characteristic of the load profile presented in previous section, specific power management strategies are developed. Since DP dominates among the operational modes of a typical OSV, an effective control approach for that should be investigated, so as to offset the instantaneous and dramatic power fluctuations. At the same time, the other operational modes (e.g. AH, TT and TS) are controlled through strategic load sharing between ESS and diesel generators. As the PV system implemented in this study is with quite slow dynamics, it is controlled by MPPT (is explained later in this subchapter), and not involved in the strategic load sharing control.

4.3.1 Peak Shaving

Compared to diesel engines, ESS has a faster dynamic response to the instant load changes. As a consequence, under DP (HDP/LDP), the diesel generators together with PV system supply the average load demands while the ESS compensates for the load fluctuations. In this way, frequent switching of the diesel engines is avoided. A peak shaving strategy meets the requirements for this scenario. Figure 36 shows the scheme of peak shaving power management system and the behavior of different power generation units under this control scenario.

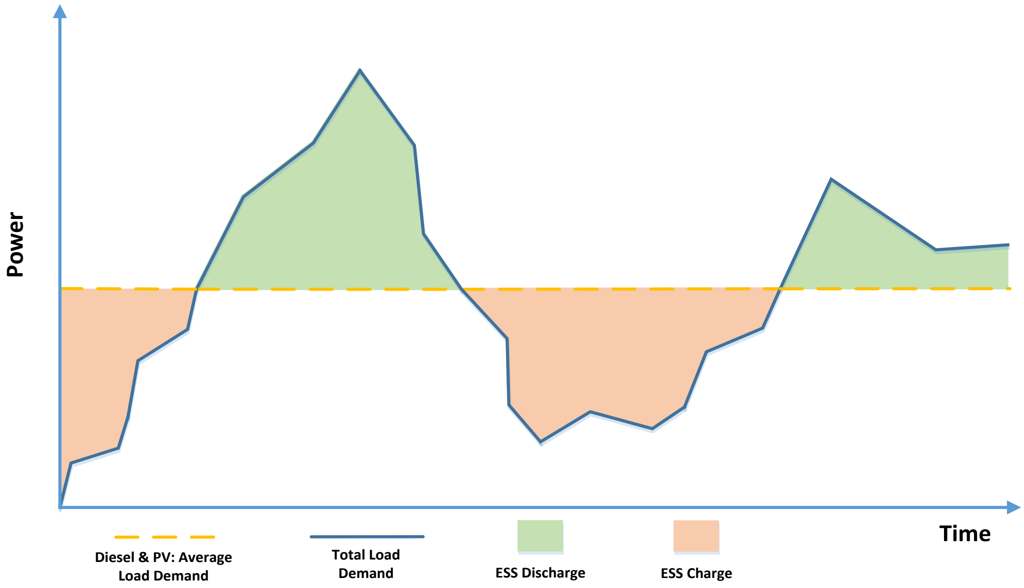


Figure 36: Scheme of peak shaving power management system

4.3.2 Strategic Load Sharing

In a DC power system, both voltage regulation and load sharing can be conducted by a voltage droop control embedded in the generators' excitation systems [32]. The load sharing control for ESS is then carried out by a control system associated to DC/DC boost converter. As shown in the Fig. 37, each of the diesel generators and ESS delivers a fraction of the total power load in a coordinated manner. In this case, the PV system contributes with a fixed power generation. The average power demands and power fluctuations are supplied by the combination of the online generation sources.

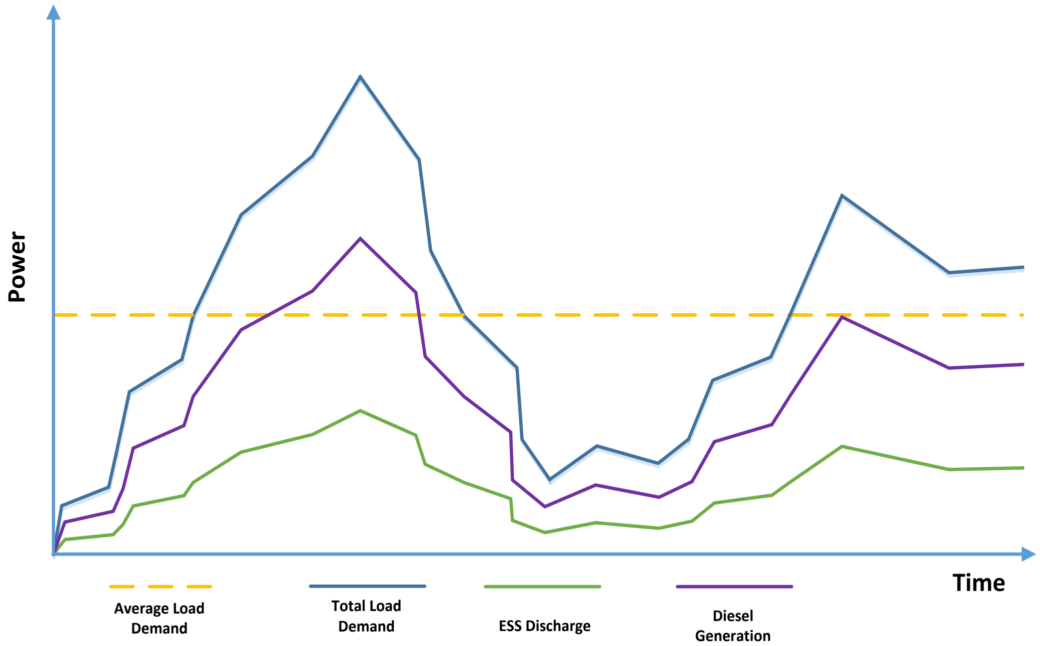


Figure 37: Scheme of load sharing power management system

In this chapter, voltage droop controllers are investigated for generator's excitation system and ESS's DC/DC boost converter. Then, it is observed that the load sharing power management strategy smooths the power consumption from diesel generation units and reduces diesel fuel expense.

Figure 38 intuitively presents the principle of a controlled exciter and converter system. Microgrid Plus System controllers, MGC600 controllers, are implemented to carry out system level communications across the electrical devices, power electronic devices and local controllers. For simplicity, load sharing and voltage regulation control between only one diesel generator and one ESS is described in Fig. 38. It should be noticed that due to the class requirement, the power load shared by each active generator is the same [52]. Deployment of MGC600 controllers into the entire marine DC microgrid system is shown in the Fig. 39.

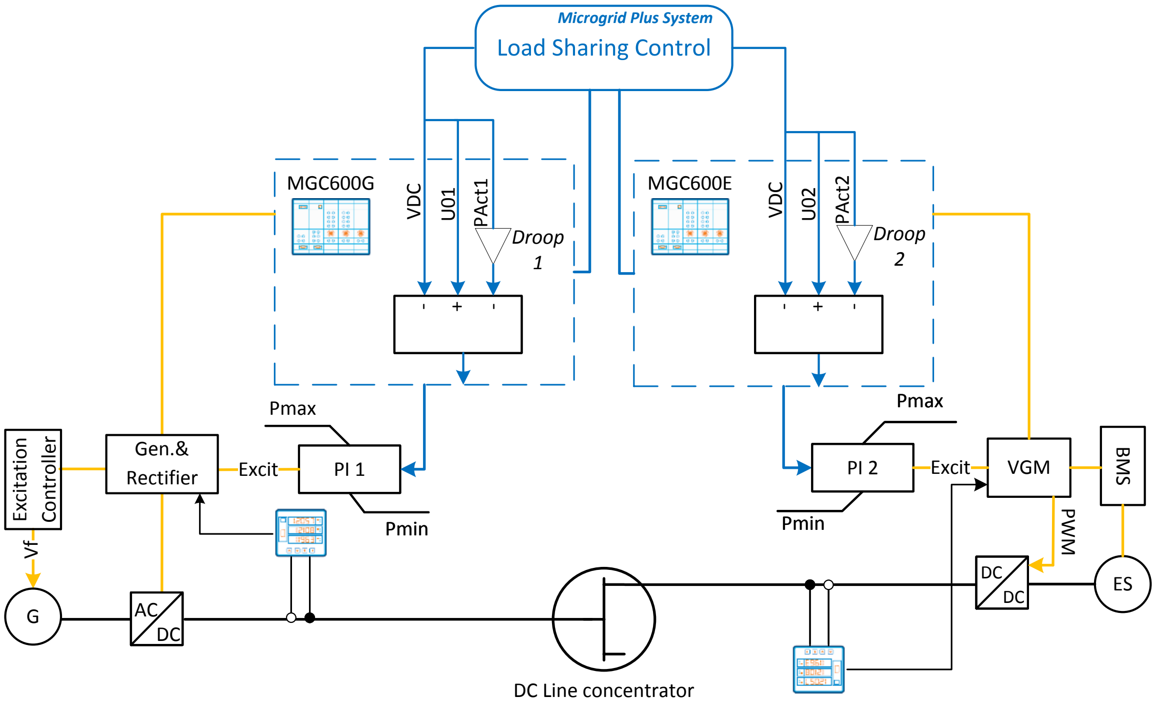


Figure 38: Controlled exciter and converter system

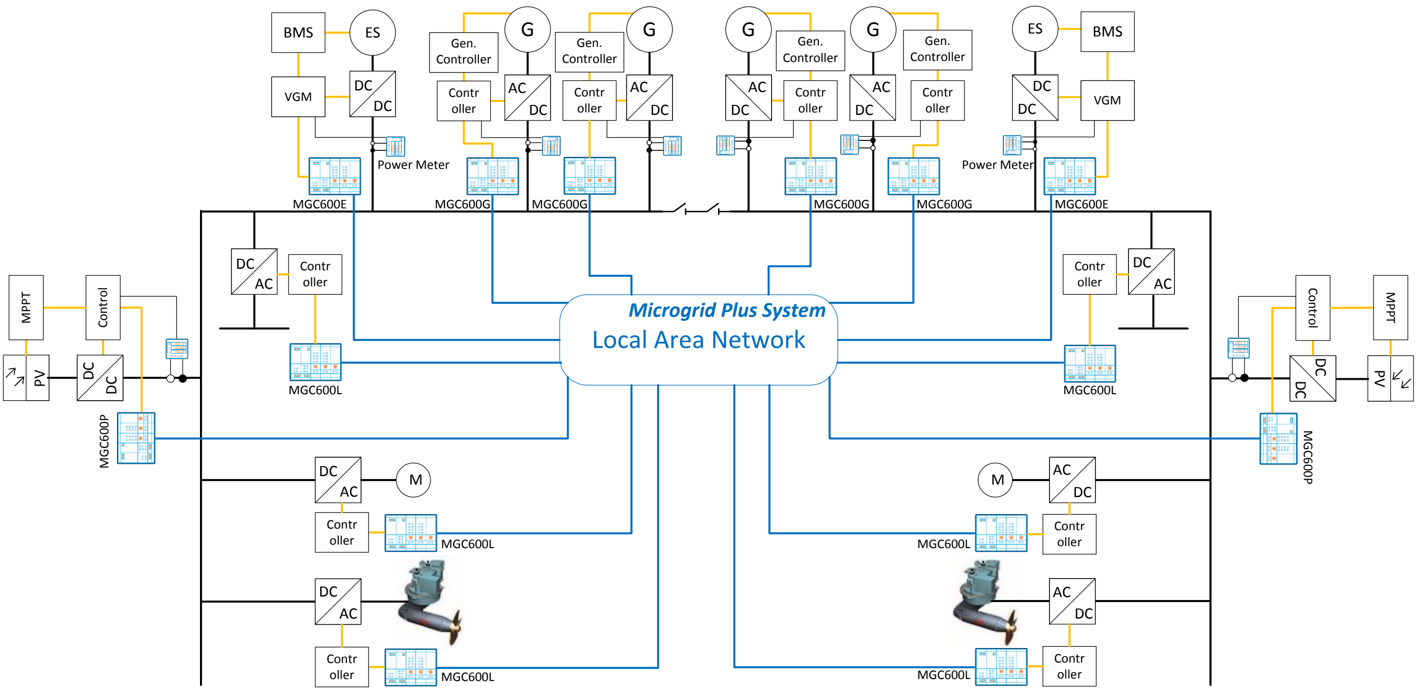


Figure 39: Deployment of MGC600 for marine DC microgrid (Isolating switch on each circuit branch is omitted)

According to the control configuration of the proposed power management strategy seen in Fig. 38, voltage droop based controllers for the battery ESS and the diesel generators are used to regulate the DC link voltage and carry out the load sharing control. The execution of the droop control is realized through a droop curve from the global "Load Sharing Control" system built up by the MGC600 controllers, and the primary controllers implement the relevant control functions locally (Fig. 38). Equation 16 describes the droop characteristic for a droop control. V_0 is the reference voltage at no load for diesel generators or ESS, and δ is the droop curve slope.

$$V_{DC}^{*} = V_0 - \delta P_{supply} \tag{16}$$

In Fig. 40 the droop characteristics of the proposed PMS, including two generators and a battery-based ESS, are illustrated. In practice, although the diesel generator units are identical, it is still hard to get exactly the same droop characteristic for each of them. Hence, different droop curve settings are observed in the figure below. Moreover, due to the existing line resistors, the physical circuit law of the electric power system has an impact on the voltage droop/load sharing control. Because of that, the droop characteristics of the generators located in different spots are not the same and need to be defined distinctly. It is assured that each online generator should share the same amount of power demand based on the defined droop characteristics.

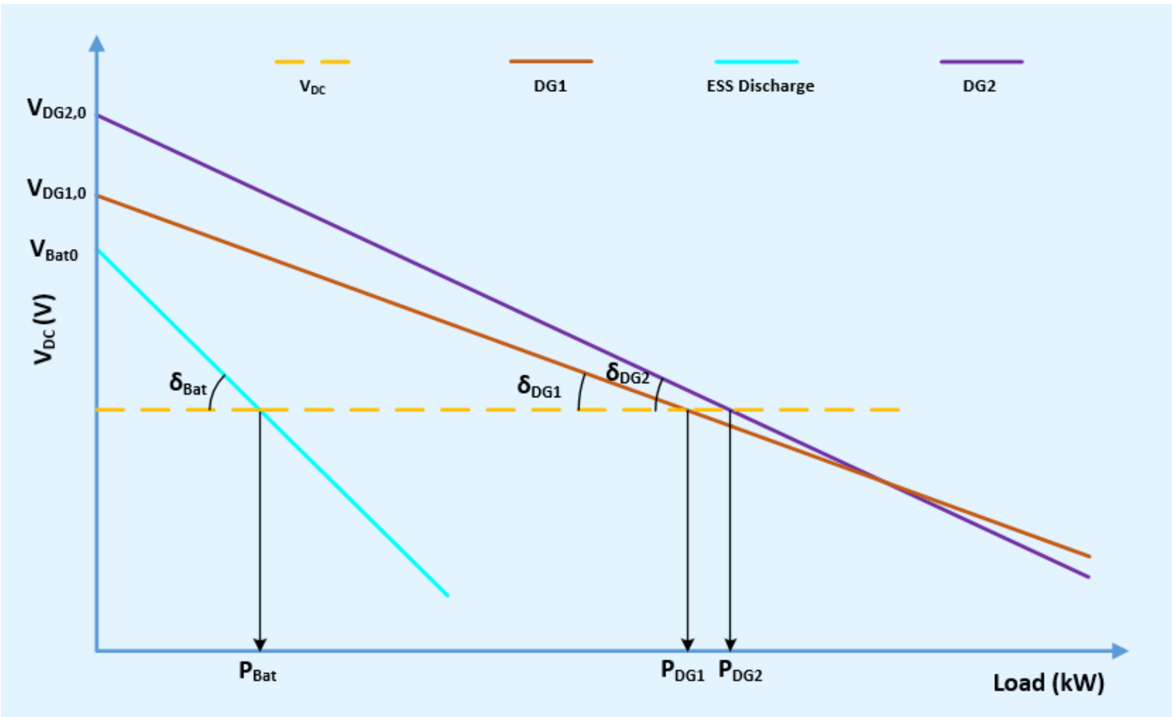
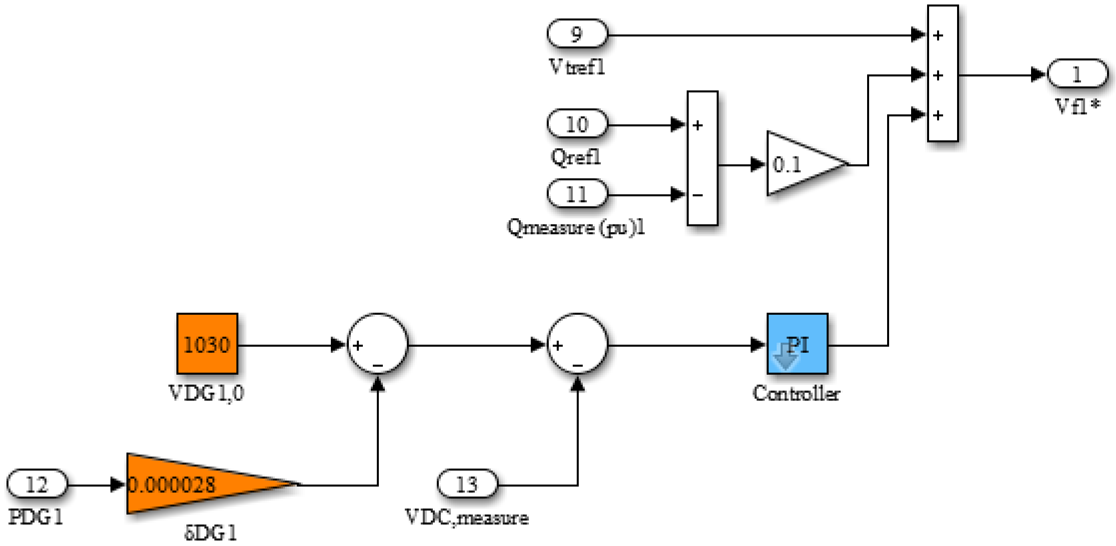
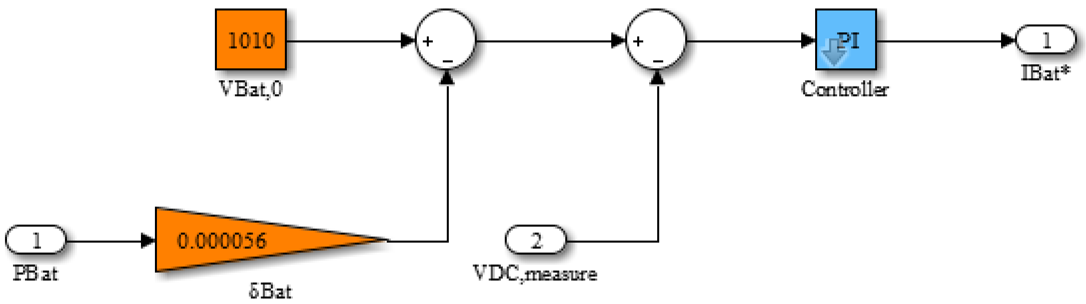


Figure 40: Droop characteristics of two generators and a battery based ESS

The selection of δ_{Bat} is crucial for the instant power exchanged between the ESS and the diesel generators. In Fig. 40, as the load changes, the smaller the δ_{Bat} is, the higher share of power load can be compensated by the ESS. Block diagrams of the two droop controllers respectively for a diesel generator and an ESS are presented in Fig. 41. PI-controllers are utilized in the control loops.



41a. Generator droop controller



41b. ESS droop controller

Figure 41: Block diagram: generator and ESS droop controllers

4.3.3 PV Control

Maximum Power Point Tracking (MPPT) control is used in PV system. When MPPT control is used, the PV power output reaches the maximum available value. Under this circumstance, the output voltage needs to reach the voltage level corresponding to the PV maximum power [53].

4.3.4 Supervisory Mode Control

For the proposed SMS, the working states of the shipboard generation system include various modes as below:

- Diesel, PV, and ESS peak shaving
- Diesel and ESS peak shaving
- Diesel, PV, and ESS load sharing
- Diesel and ESS load sharing
- ESS charging, PV and diesel load sharing/voltage control

The supervisory mode for the proposed power management system monitors the load profile and decides the initial number of online diesel generator. The working state of the generation system is decided based on onboard load demand and resource availability (PV and battery SOC). This supervisory mode control is illustrated in a flowchart presented in Fig. 42.

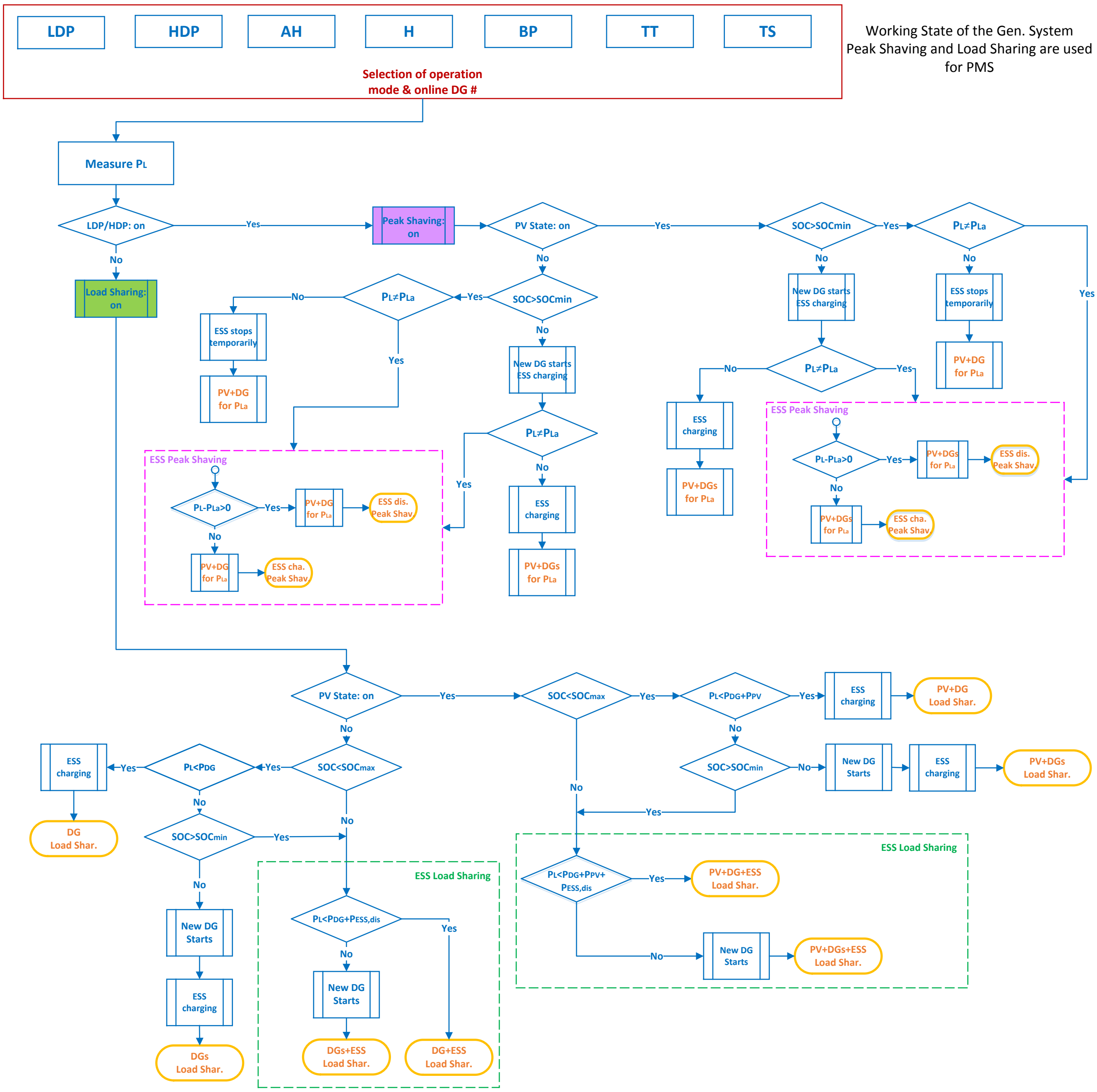


Figure 42: Supervisory mode for power management system

In conclusion, Chapter 4 discusses the methodologies used in this thesis for configuring, controlling and operating shipboard microgrid system. In the following chapter, four test cases are validated in MATLAB Simulink platform and the time-domain simulation results are analyzed. After that, the proposed SMS is validated in terms of operation stability and power management strategies.

5 Component Modeling and System Simulation

In this chapter, the component modeling is done and time-domain simulations are carried out in MATLAB Simulink platform. First some of the models of power electronic devices are presented. After that, definition of each test scenario is presented and explained in details. Then, the results of the simulations are analyzed.

5.1 Component Modeling

In this subchapter, some of the modeling blocks are introduced. It should be noted that because of the different dynamic characteristics of the mechanical and electrical components, detailed switching level modeling approach is not carried out in order to avoid large simulation times [54].

5.1.1 Synchronous Generator-Rectifier System

A model of a synchronous generator is chosen from the Simulink library. The block mask parameters are specified according to the data provided in table 8 in Chapter 4.

Considering an uncontrolled three-phase diode bridge rectifier, a Universal Bridge block from Simulink library is parameterized for the purpose of modeling. In the case of using uncontrolled rectifier, the voltage regulation is implemented by the excitation system.

The output voltage level after the rectifier is expressed by equation 17 [55]. The voltage level of the load bus is set to be 1000 V DC with a variation tolerance of ±10% [52, 58]. Thus, the line-to-line voltage of the synchronous machine, V_{LL} , is parameterized as 750 V. In reality, due to the line losses exist in the distribution network, the load bus DC voltage level is slightly lower than the designed 1000 V.

$$V_{dc,rectifier}^{max} \approx \frac{3}{\pi}\sqrt{2}V_{LL} \tag{17}$$

5.1.2 Diesel Engine

The diesel engine system modeled in this thesis includes an excitation system, a voltage regulator, and a subsystem including governor & diesel engine. The governor acts as a connector between the generator and the diesel engine. It provides the generator with an output of mechanical power P_m by means of executing a speed control loop. Figure 43 shows the block diagram of the modeled diesel engine.

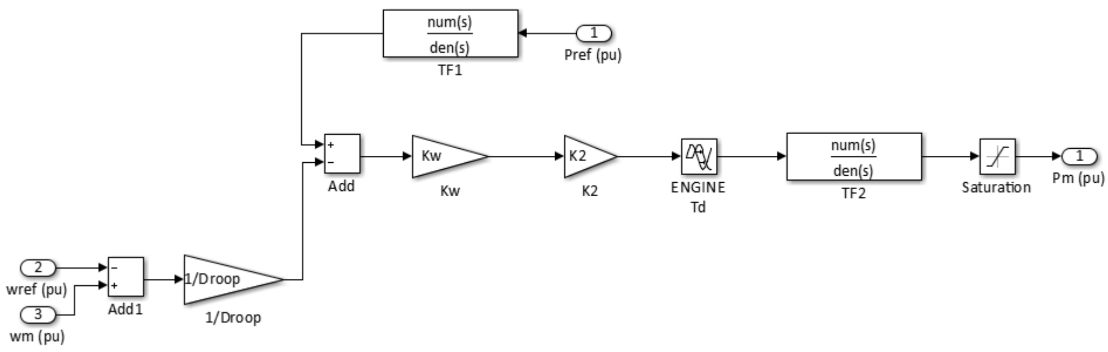


Figure 43: Block diagram of diesel engine

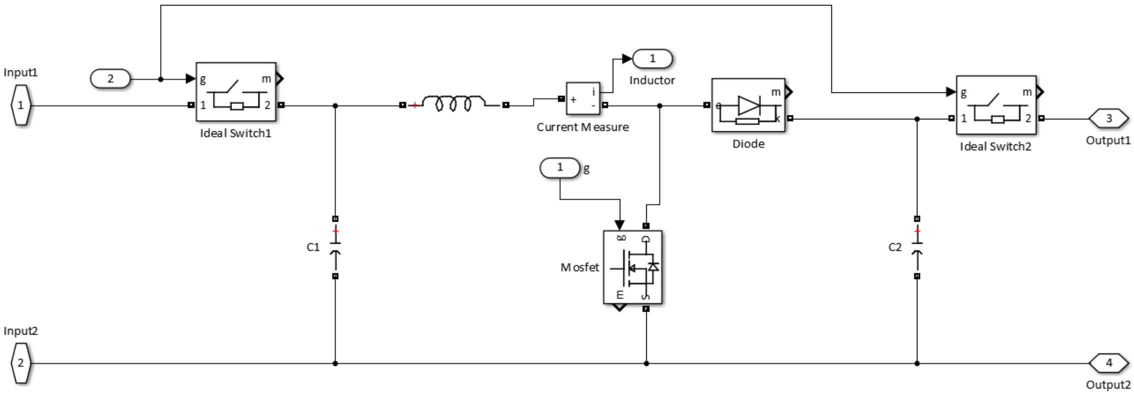
There are several different ways of modeling a diesel engine, and this thesis implements one approach as shown in the Fig. 43. The diesel engine is modeled approximately by a time delay τ_d. The engine mechanical power P_m is calculated by equation 18. ω_m is the engine rotor speed, and T_m is the generated torque.

$$P_m = T_m \cdot \omega_m \tag{18}$$

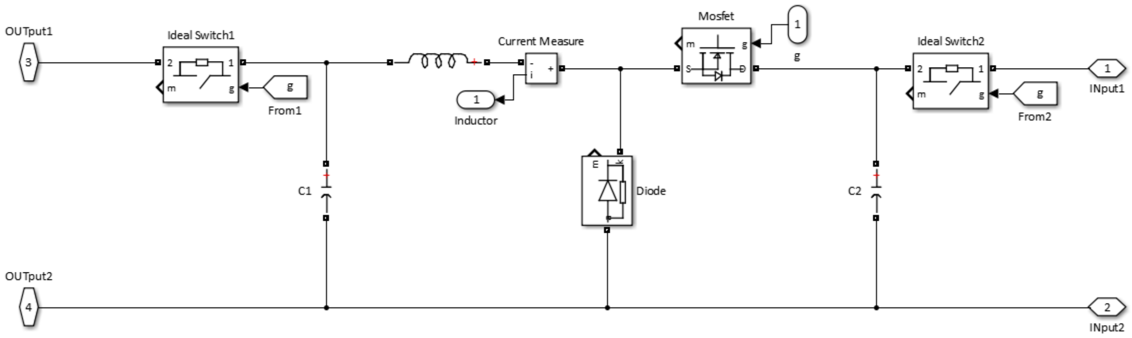
5.1.3 Energy Storage System

The battery bank of the ESS is modeled by Simulink Battery block. The parameters are set according to the data given in table 10 from Chapter 4. A bidirectional DC/DC converter is set up for connecting the battery bank with the DC distribution network.

Topology of a full-bridge boost/buck converter is implemented in this thesis [56]. As shown in figure 44a, the boost mode of the bidirectional DC/DC converter operates when inductor current flow into the DC bus of the SMS. The switches used are the type of a MOSFET and a diode. A buck converter (Fig. 44b) is paralleled with the boost converter, and it operates while the boost mode is switched off. The switch on/off of the buck mode is controlled based on the battery SOC and the instantaneous load profile.



44a. Boost mode



44b. Buck mode

Figure 44: Topology of bidirectional converter

5.1.4 PV System

As discussed in Chapter 4, the PV output controller is modeled based on MPPT. A DC/DC boost converter is modeled to connect the lower-voltage DC energy source, i.e. PV, to the higher-voltage SMS DC link. The topology of the PV DC/DC booster is similar to that of the boost mode of the ESS DC/DC converter (Fig. 44a).

5.1.5 Constant Power Load

The detailed load profile of the OSV is analyzed in Chapter 4. Note that the propellers and thrusters account for the largest power consumptions onboard. They are linked to the DC bus via DC/AC inverters. Since this kind of loading system can withdraw constant power from the DC link bus at any voltage level, modeling of the loads is then based on constant power load (CPL) approach [57].

The mechanism of modeling CPL in Simulink is to use a Controlled Current Source block. The controlled current source is fed by the signal of demanded current value under certain DC voltage level. The demanded load current is determined by equation 19.

$$I_{load} = \frac{P_{load}}{V_{dc}} \tag{19}$$

5.2 Test Scenario Definition

The OSV normally operates under seven different modes. The operational modes are introduced in Chapter 4. Two main categories of the operating modes are made for defining test scenarios: Dynamic Positioning (high dynamic positioning and low dynamic positioning) and Transiting & Sailing (anchor handling, transit towing, transit supply, bollard pull and harbor). In this thesis, Peak Shaving strategy is implemented by PMS to manage power flow for Dynamic Positioning mode, while Load Sharing strategy is used for Transiting & Sailing mode. Figure 45 shows the overall setups of the simulated SMS in Simulink.

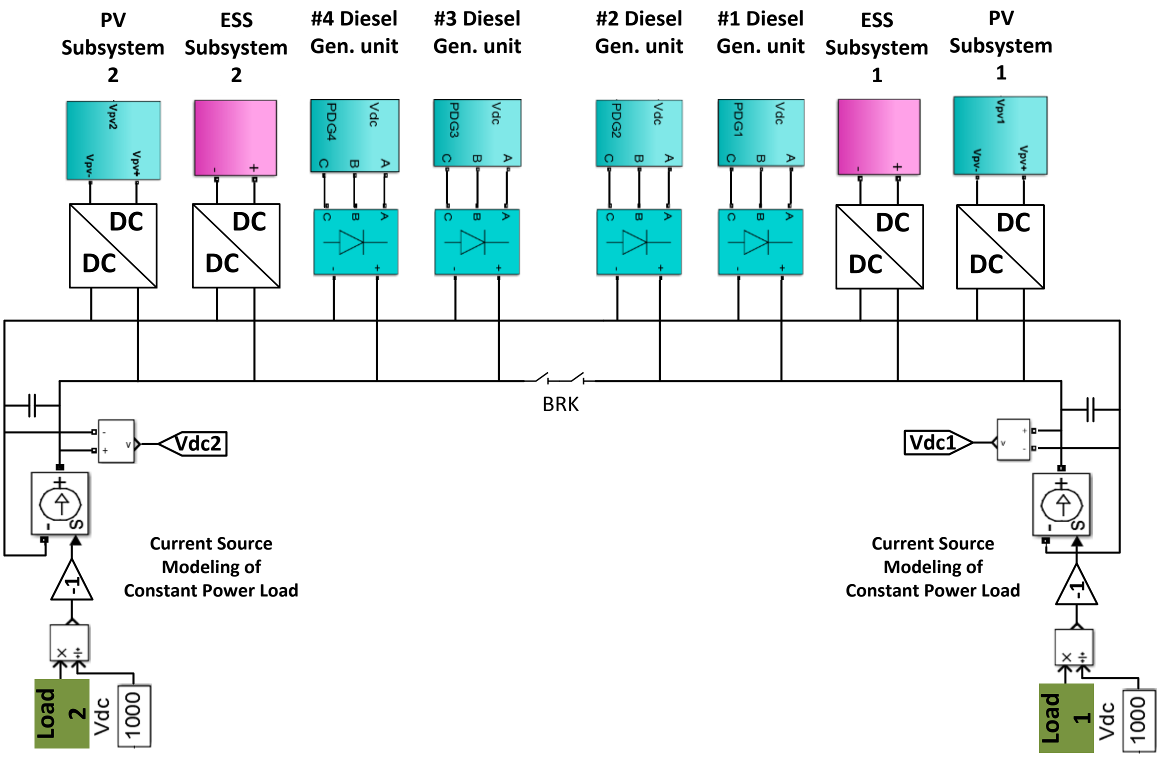


Figure 45: Overall setups of the simulated SMS in Simulink

In this subchapter, four test cases are defined to validate the design and the proposed control strategies. The four scenarios are based on the realistic load profile shown in table 9 (Chapter 4). They can generally represent the characteristics of each category of the operating modes. In the simulation process, the initial SOC of Scenario 1, 2 and 4 is 80%, and the simulation periods of 15 ~ 70s and 50 ~ 150s are taken to represent the steady states of the Scenario 1/2/4 and Scenario 3 respectively. Descriptions of the test scenarios are listed below (working state of the generation system follows the procedures stated in Fig. 42 in Chapter 4):

- **Scenario 1** SMS operates under AH mode: PV system operates with MPPT control; #1 and #4 diesel generation units, together with ESS, operate under strategic load sharing

- **Scenario 2** SMS operates under TS mode: PV system operates with MPPT control; #1 and #4 diesel generation units operate with voltage droop control/load sharing control; ESS is under charging mode

- **Scenario 3** SMS operates under TT mode: PV system operates with MPPT control; Initially #1 and #4 diesel generation units, and ESS operate with strategic load sharing; At 70s, SOC drops below 20%, #2 and #3 diesel generation units start up and ESS changes into charging mode; Since then, #1 ~ #4 diesel generation units operate with voltage droop control/load sharing control till ESS charging is finished at 133s; Then working state gets back to the initial status

- **Scenario 4** SMS operates under HDP mode: PV system operates with MPPT control; #1 and #4 diesel generation units operate with voltage regulators, and together with PV system, supply the average power load of 2046 kW; ESS supplies or absorbs power flow to compensate the load fluctuations

5.3 Simulation Results

This subchapter presents the simulation results of the four test cases defined in previous section. Simulation results verify the proposed power management strategies and validate the system stability under four defined scenarios with the proposed control schemes.

5.3.1 Scenario 1 - SMS Operating under AH Mode

In this case, the ESS is under discharging condition (Fig. 46). Diesel generation units, PV system, and the ESS together supply the power load demands through strategic load sharing. The power flows of ESS, #1 and #4 diesel generation units are managed by load sharing control. Figure 47 illustrates the power flows of the generation sources in steady working status. The droop characteristics of the voltage controllers determine the percentage that shared by each of the sources under the control of load sharing strategy. In this scenario, the droop characteristics should be selected to keep the diesel engines working within their optimal operation windows (between 60% ~ 100% of each rated power). PV system operates with MPPT control supplying maximum available power that is constant during the simulation process.

While load sharing strategy controls the power flows, the voltage level of the DC link is regulated by this strategy at the same time. Figure 48 presents the output voltage levels of online generation units and also the DC link voltage. It reflects that, with the control of strategic load sharing, the SMS operates stably under various loading levels with moderate fluctuations. The voltage ripples caused by the variations in load are controlled within ±5% of the rated voltage level. The average time constant is 3s, which means the system gets back to the steady state within 3s after each transient.

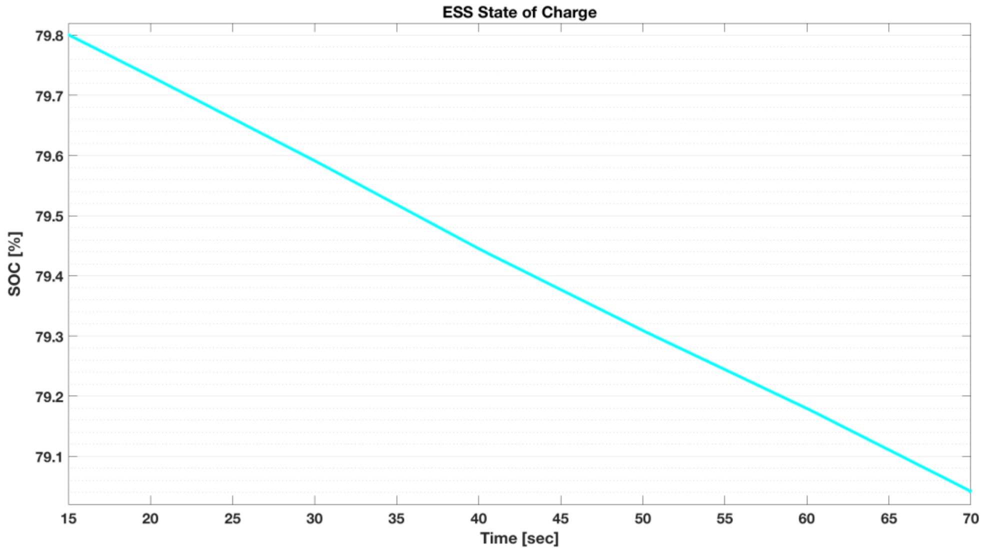


Figure 46: SOC of energy storage system of scenario 1: AH mode

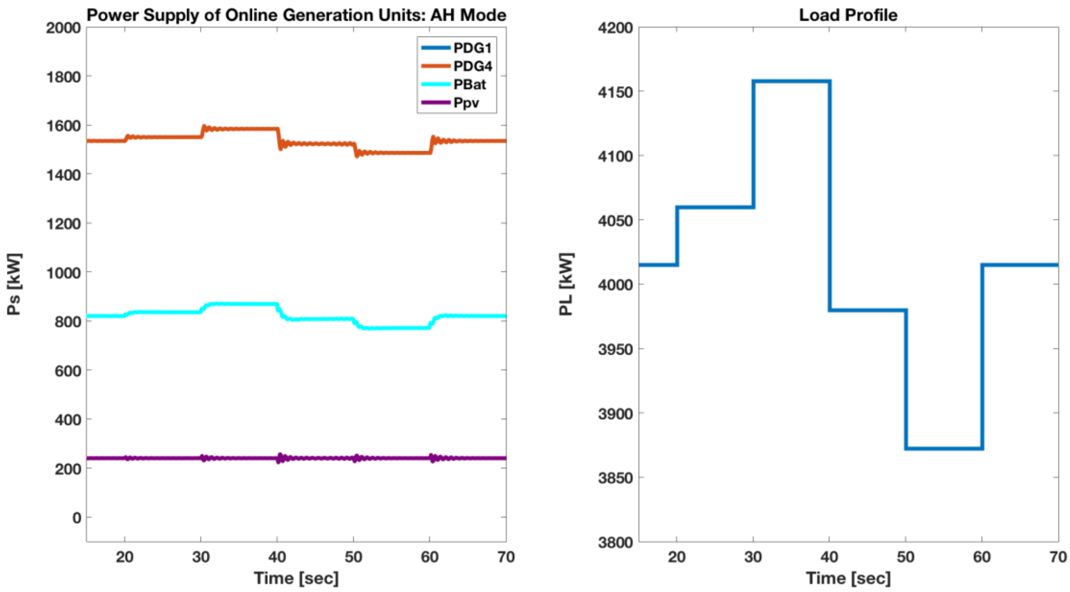


Figure 47: Power flow of scenario 1: AH mode

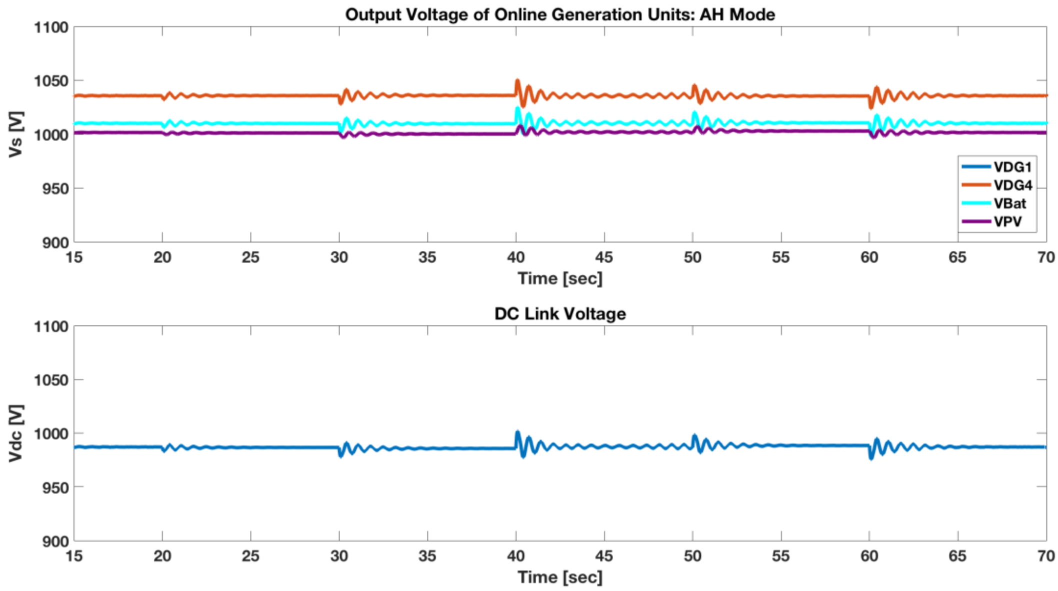


Figure 48: Voltage level of scenario 1: AH mode

5.3.2 Scenario 2 - SMS Operating under TS Mode

Working in TS mode (low power load demand), the ESS is basically under charging condition (Fig. 49), so as to maintain the diesel engines operating over 60% ~ 100% of the rated power. The DC link voltage is controlled by droop structures of the generator sets. Figure 50 depicts the power outputs of all the online generation units. It should be noticed that, in order to maintain the optimal working windows for diesel engines, the charging power is set to be 1000 kW if load demand is higher than 2 MW, and is 1430 kW (rated value) if load demand is less or equal to 2 MW. Those two thresholds are set empirically and can be optimized by a certain algorithm. There is no obvious fluctuation occurring in the power flow, which means that the SMS sustains operational stability under this scenario.

In Fig. 51, larger voltage ripples are observed on the DC link than those of AH mode, but the variations are still controlled within the tolerance: the voltage variations are controlled within ±5% of the rated voltage level [52, 58]. The average time constant of this case is 5s, which means the system gets back to the steady state within 5s after each transient.

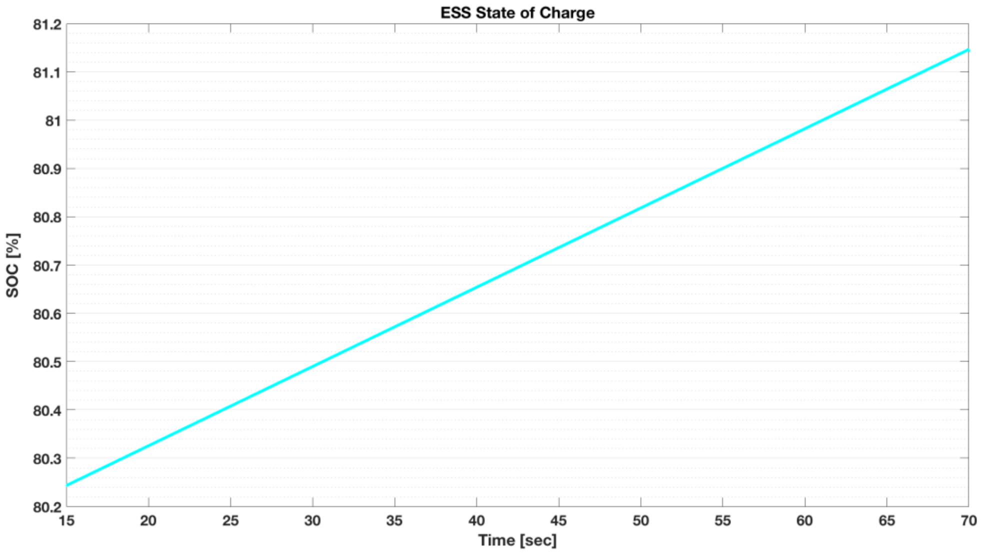


Figure 49: SOC of energy storage system of scenario 2: TS mode

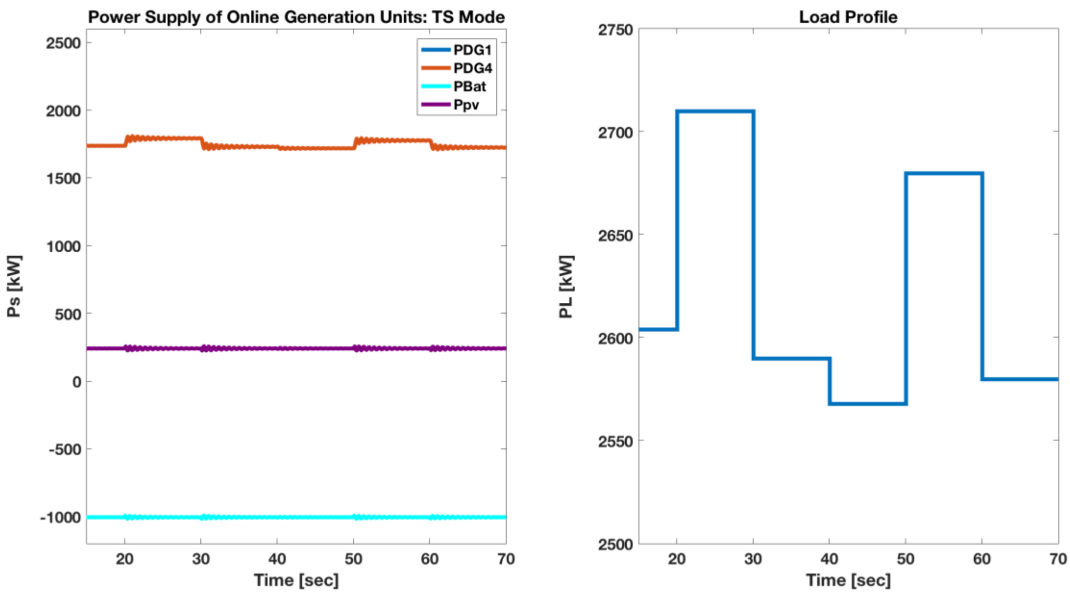


Figure 50: Power flow of scenario 2: TS mode

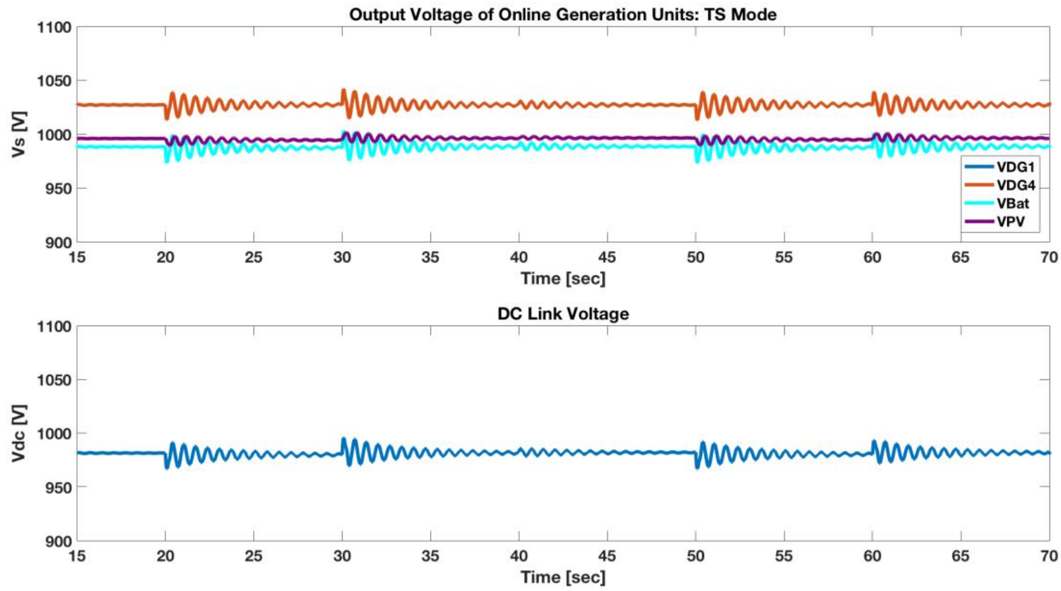


Figure 51: Voltage level of scenario 2: TS mode

5.3.3 Scenario 3 - SMS Operating under TT Mode

When an OSV operates under TT mode, it experiences the highest power load demand. The initial number of online diesel generators is the same as in mode AH and TS. However, due to its high average load demand, the spinning reserve margin becomes low if the same amount of diesel generation is withdrawn, especially when the SOC drops below 20%. Consequently, in this scenario, starting up new engines is tested.

In the beginning, #1 and #4 diesel generation units are online with the ESS and PV system. Initially, the diesel generation units and ESS operate with strategic load sharing. At 70s, battery SOC drops below 20%, so ESS gets into charging mode in order to keep the battery bank working within its operational capacity window. Meanwhile, #2 and #3 diesel generation units start up. After that, #1 ~ #4 diesel generation units operate altogether under voltage droop control/load sharing control. At 133s, the charging of ESS is done (theoretically, charging is done till SOC becomes 100%, but in the simulation process, the threshold is set to be 21.5%, so as to observe the changing status earlier). From then on, the working state of the SMS gets back to the initial status. The described SOC changing status is presented in Fig. 52.

The power flows of TT mode are presented in Fig. 53. As new engines are started at 70s, a significant power impulse is observed. Approximately after 3s, the system gets back to the steady state again. As mentioned in Chapter 4, the droop structures of the diesel generators need to be slightly different. After adjusting the droop characteristics, all the four diesel generators can supply the same percentage of load during the ESS charging period. For the rest of the simulation process, the working states of the power generation units follow the same patterns as in the AH mode.

Figure 54 shows the output voltage levels of different generation sources and the DC link voltage level as well. Significant voltage fluctuations can be seen when the new engines are started up and shut down. According to the Power Quality for the

Electrical Contractor, long duration voltage variations affect the characteristics of the steady state voltage and long duration voltage variations are considered to be present only when the limit is exceeded for greater than 1 minute [58]. Since in this scenario these transients are declined fast within 3 seconds after they appear, the start-up/shut-down does not change system characteristics and the power quality is not affected.

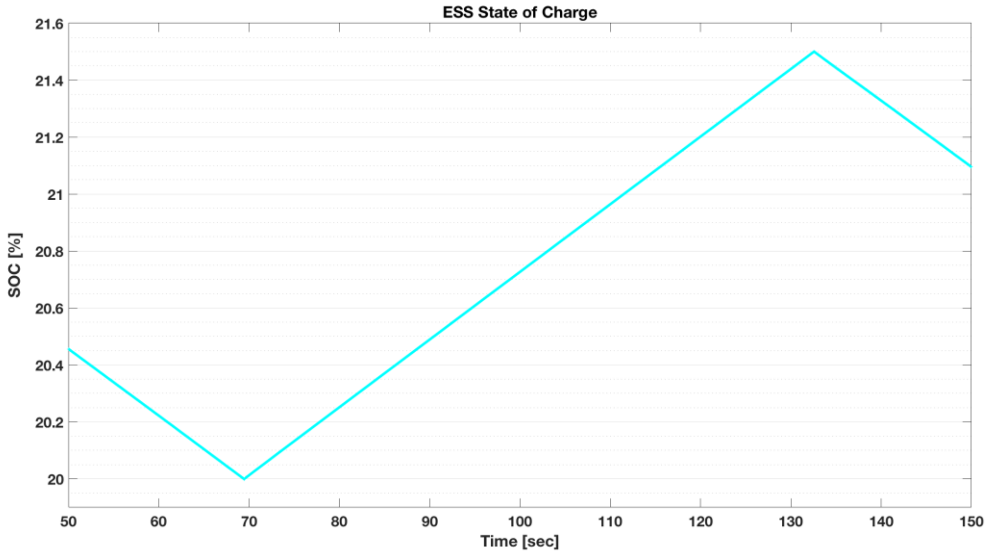


Figure 52: SOC of energy storage system of scenario 3: TT mode

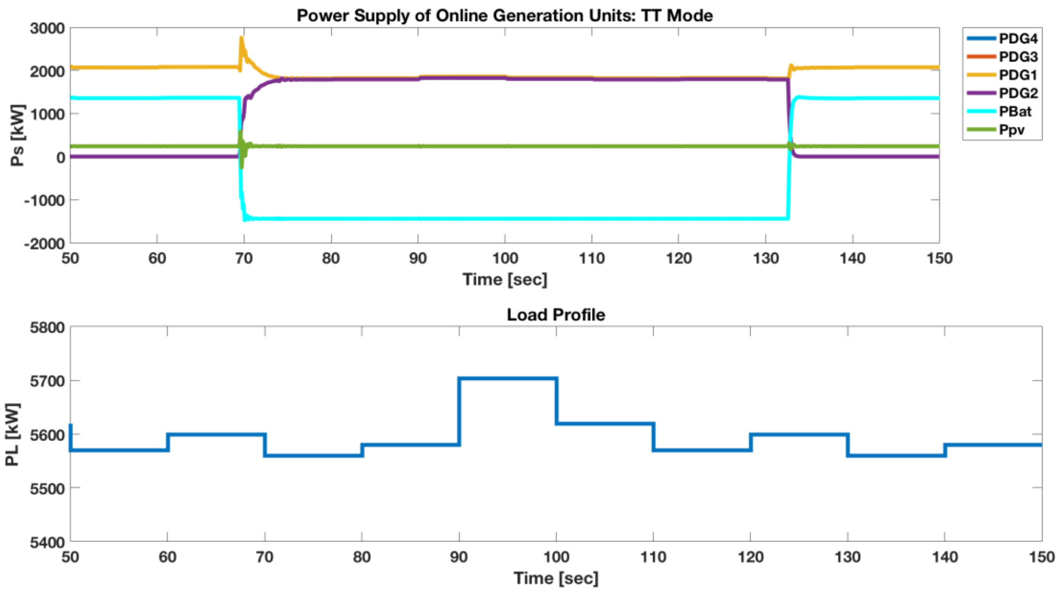


Figure 53: Power flow of scenario 3: TT mode

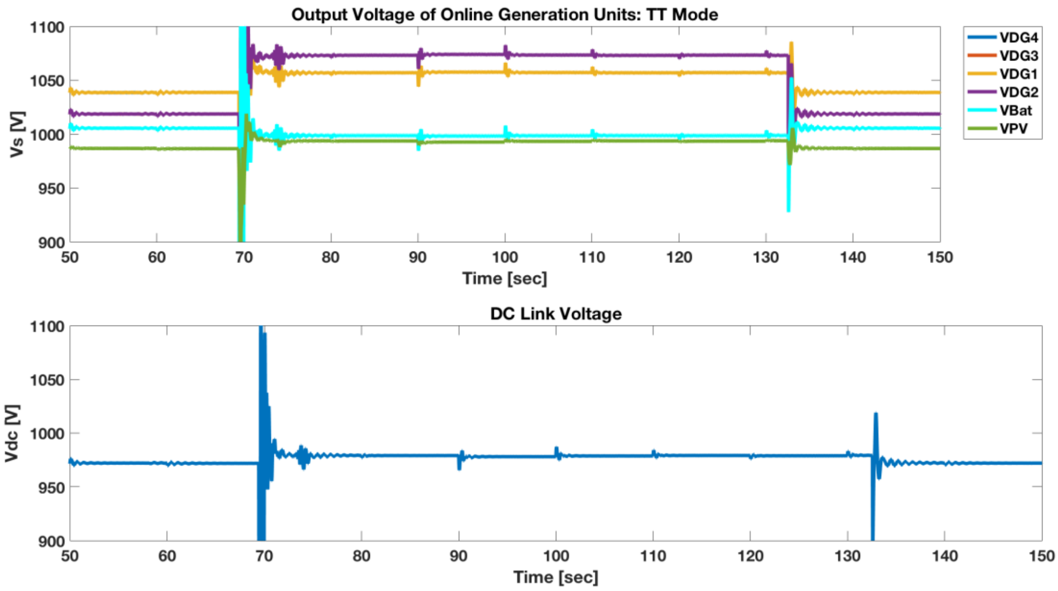


Figure 54: Voltage level of scenario 3: TT mode

As a conclusion, the proposed system can promptly eliminate the impacts of the transients introduced by start-up/shut-down of new engines. Because of that, the stability and power quality of the SMS are validated through this test scenario.

5.3.4 Scenario 4 - SMS Operating under HDP Mode

In this section, the PMS operated with peak shaving control is tested. The #1 and #4 diesel generation units are operated with voltage regulators, and together with PV system, they supply the average power load of 4080 kW. In this case, the ESS is controlled to absorb or inject active power to compensate the load fluctuations. The SOC of the energy storage system reflects the charging and discharging status intuitively. As seen in Fig. 55, under charging mode, the slope of the SOC curve is positive, and when the ESS is discharging, the slope is negative. To explain the characteristics of the peak shaving strategy, figure 56 shows the power flow patterns of all the generation sources. It presents that the diesel generation units and PV system produce constant power outputs, while the ESS delivers fast dynamic responding to large load fluctuations.

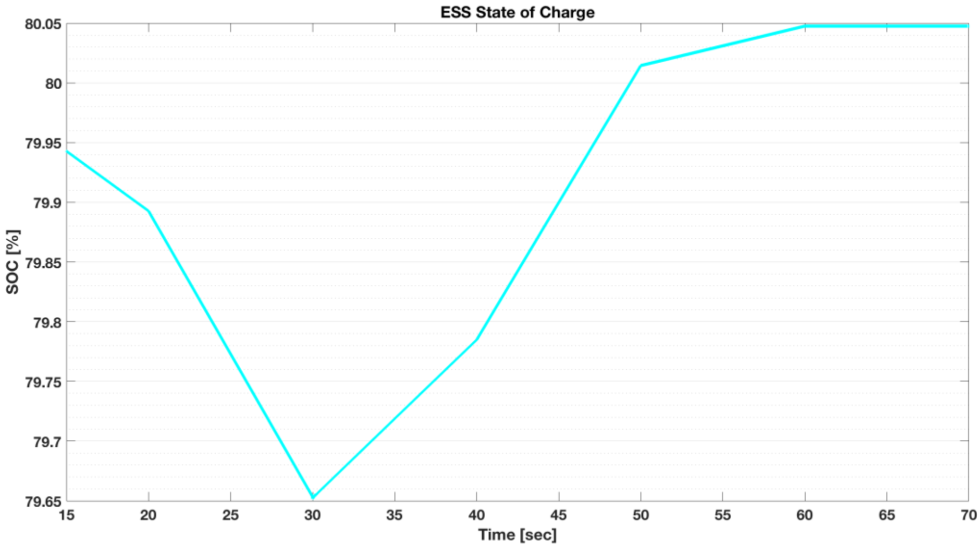


Figure 55: SOC of energy storage system of scenario 4: HDP mode

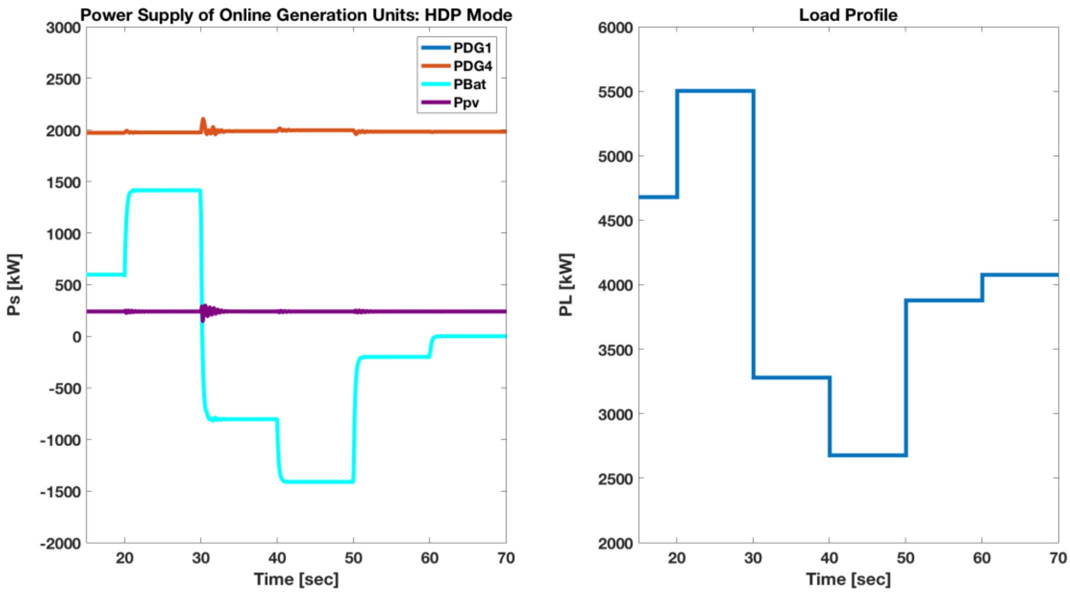


Figure 56: Power flow of scenario 4: HDP mode

Figure 57 illustrates the voltage levels of the generation outputs and the DC link. As shown in the figure, due to a dramatic load fluctuation, a significant voltage transient appears at 30s and is diminished within 4s. As the load fluctuation gets lower (e.g. at 50s), the voltage transients are declined faster.

In short, the peak shaving strategy sustains the operational stability of the SMS when significant load fluctuations occur. The fast response of the ESS to the system-level transients is validated and the frequent variations in the outputs of diesel generation units are avoided.

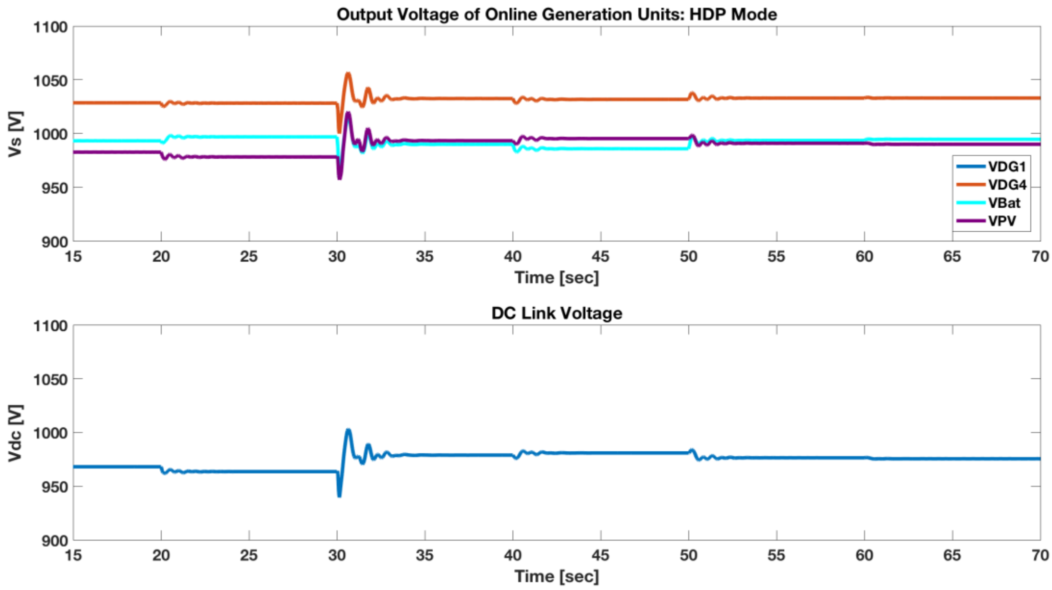


Figure 57: Voltage level of scenario 4: HDP mode

To summarize the simulation results, the PMS is simulated offering strategic load sharing and peak shaving. It is tested through four specific scenarios based on MATLAB Simulink. The simulation results show that the SMS can work stably under different load profiles. In addition, with proper power management strategies chosen for different operation modes, the operation of SMS can be shifted between different states without impacting the performance and stability of the system. Also, the strategic power management eliminates the voltage sags caused by engine start-up/shut-down, so that the power quality is not affected. Last but not least, the PMS maintains the level of SOC through charging control under low power load demand (e.g. TS mode), which allows the ESS to maintain certain redundancy and supplies sufficient power for implementing the proposed PMS.

6 Conclusion and Future Work

In this thesis, the challenges and feasibility of implementing microgrid for marine vessels are investigated. Peak shaving and load sharing power management strategies are formulated with integration of energy storage and PV, to islanded marine microgrid with diesel generators. Time domain simulations are carried out in MATLAB Simulink platform to validate the main concepts. The conclusions of the thesis are:

1. It is possible to integrate renewables and energy storage to islanded marine grids and operate them as microgrid.

2. The microgrid implementation can be achieved by connecting microgrid controllers to the existing marine control platforms, e.g. 800xA.

3. The reliability of the microgrid system structure can be improved with different switchyards however the cost would be much higher due to high number of breakers.

4. The microgrid control functions developed in this thesis can efficiently achieve peak shaving and load sharing in the marine islanded grid for various loading scenarios.

5. The simulation results with the test system validate system stability of the shipboard microgrid system with various loading conditions defined in the four test scenarios.

For the future work, the following topics can be studied:

1. Calculation of the fuel consumption in the proposed SMS can be done to quantify the savings of the system.

2. In order to facilitate the network communication system (Mplus_800xA) in the proposed SMS, studies on automation control and wireless communication can be carried out.

3. It would also be interesting to implement other control functions in the proposed SMS, for instance, load shedding and restoration under fault conditions.

4. Optimal sizing of the ESS and PV system with considerations of economic factors can be conducted.

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Appendices

A

Table 6: Feasibility Analysis - ABB microgrid solutions and availability of modification for marine applications from standard microgrids

ABB Solutions	level	Description	Common Practice	Functions	Operation Conditions Compatible with Marine	Feasibility
EssPro™ Battery Energy Storage System	ASSET	Together with BMS, the EssPro™ ensures modular design and flexible product, proprietary algorithms enable a variety of storage applications, and built-in redundancy and protection system enable lowest cost of ownership	1. Power capacity of min. 100 kW up to n × 30 MW (each unit) 2. Energy capacity of min. 200 kWh up to n × 7.2 MWh (each unit) 3. battery DC voltage range is up to 1.2 kV	1. maintain efficient transmission and distribution by providing active and reactive power control 2. BESS including added voltage support and grid stabilization, decreases in transmission losses and congestion 3. optimization of the renewable energy output through capacity firming and smoothing	charging/discharging power to the grid when energy output varies, or during unstable events, such as extreme weather conditions	Yes

UNITROL® automatic voltage regulators (AVR)	ASSET	enable voltage regulation of electrical propulsion and auxiliary supply for marine, diesel electric locomotives, and synchronous motors	1. Built-in control software functions 2. a compact and robust AVR for excitation current up to 40 A, obtaining Ethernet-based fieldbus interface	enable wide range of power input voltage, both for AC and DC input. One of the applications of UNITROL® 1000 is for marine electrical propulsion and auxiliary supply	UNITROL® AVR and SES offer solutions for any type and size of power plant. UNITROL® 1000 provides compact and reliable solutions	Yes
Static excitation systems (SES)	ASSET	In DC distribution system, the voltage regulation and load sharing are both conducted by the generator excitation system				
Microgrid Plus System	Microgrid	It is a distributed control system for microgrids. It is a specially-designed network control system. It is a key technology responsible for coordinating the operation of hybrid power stations and successfully stabilizing and integrating renewables into microgrids	1. MGC600 microgrid controller package is used to manage and automate distributed power generation systems	1. maximize fuel savings 2. optimize use of renewable energy 3. guarantees optimum loading and spinning reserve in fossil fuel generators 4. distributed logic enhances reliability and scalability for future system expansions		Yes
PowerStore	Microgrid	PowerStore is a flywheel and battery based grid stabilizer	1. It consists of flywheel energy storage or batteries energy storage 2. power converter system (AC-DC-AC converters) and operator interface (operator interface is used to monitor the flywheel or battery and converter components and to provide access to historical data) 3. PowerStore can be configured in three different sizes: 500, 1,000 and 1,500 kW	1. Frequency Droop Control[A/I] 2. Voltage Droop Control[A/I/G] 3. Power Factor Correction [I/G] 4. Anti-Islanding [I/G]: Monitor grid and provide anti-islanding protection if required and inform M+ 5. Automatic Recharge: Recharge during optimal time 6. Peak Shaving	For isolated marine operation, reliability and stability can be sustained by using PowerStore; The inland PV/Diesel microgrid configuration implements PowerStore	Yes