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Adaptive Power Management of Hierarchical Controlled Hybrid Shipboard Microgrids

MUHAMMAD UMAIR MUTARRAF[1], (Member, IEEE), YAJUAN GUAN[1], (Member, IEEE), YACINE TERRICHE[1], CHUN-LIEN SU[2], (Senior Member, IEEE), MASHOOD NASIR[1], JUAN C. VASQUEZ[1], (Senior Member, IEEE), AND JOSEP M. GUERRERO[1], (Fellow, IEEE)
[1]Center for Research on Microgrids (CROM), Department of Energy Technology, Aalborg University, 9220 Aalborg, Denmark
[2]Department of Electrical Engineering, National Kaohsiung University of Science and Technology, Kaohsiung 807618, Taiwan

Corresponding author: Chun-Lien Su (cls@nkust.edu.tw)

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ABSTRACT Shipboard microgrids (SMGs) are distinguished by the heavy propulsion system that can vary largely in a short time. Consequently, this variation shifts the optimum operating points of the diesel engines that leads to increase the overall emissions and operational costs. Moreover, power fluctuations caused by the dynamic loads such as propulsion motors along with the lack of cold-ironing facilities at both ends of seaports make it even worse. Therefore, the application of energy storage systems (ESSs) with proper coordination is becoming very popular for ships to improve the energy management, and thus decreases the fuel consumption. The aim of this paper is to firstly highlights different architectures of SMGs and the benefits the ESS can brings into them, then proposes an enhanced hierarchical control-based energy management scheme that is suitable for SMGs operations during an islanded and grid-connected operation. The proposed method based on the ESSs supports the diesel generators to enable them to operate in the optimum window recommended by the diesel engines company, which significantly decreases fuel consumption, operational costs, and emissions. Furthermore, to provide a linkage between SMG and the grid during port stays, conventional $P-f$ and $Q-V$ droop control strategy is adopted to import and export power to the seaport load or the grid for emergency purposes referred to in this study as Ship-to-X operation. The enhanced hierarchical control is capable of optimally shifting the modes for efficient and reliable operation and reducing specific fuel consumption. The performance of the proposed scheme is adopted and validated with satisfactory results of a practical hybrid SMG in a MATLAB/SIMULINK environment.

INDEX TERMS Droop control, power-sharing, quasi-load-leveling, shipboard microgrids, Ship-to-X.

I. INTRODUCTION

The varying fuel prices and strict regulations introduced by the international marine Organization have urged shipbuilders to move towards energy-efficient and greener resources following the footprints of the terrestrial energy sector, where an increased amount of integration of renewable energy sources (RES) helps in minimizing the emissions [1]. Hence in terms of sources, conventional internal combustion engine (ICE) based shipboard microgrids (SMGs) are moving towards All-electric ships (AES), i.e., 100 % battery-equipped or Hybrid electric ships (HES), i.e., partial battery, to minimize emissions, noise pollution, and improved fuel consumption. Although installing the battery is not new in ships, it's already been used for several years for providing backup power to the auxiliary power supply, starting of generators, etc., and acting as an uninterruptible power supply (UPS) purpose rather than for traction purposes. But the rating of such battery packs (BPs) is very small (a few kWh) whereas the capacity of BPs in AES falls in the range of several kWh to a few MWh range, and for HES, it starts from several kWh [2]. The main challenge in the transition from ICE-based ships to AES is the lack of available charging infrastructure at ports, limiting its use in a broader perspective [3]. Another challenge is the cost, the lifetime, weight/volume of the battery (Lithium-ion),

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which further is an obstacle in its use for longer route ships, particularly ferries. Therefore, hybrid SMGs have more potential to be the predominant source for future marine transportation.

Further, if we classify based on architecture, most of the conventional SMGs are AC-interfaced with few exceptions where modern battery-equipped ships tend to move towards DC-based. However, whether it's AC-based or DC-based SMG where AC, DC sources, and loads coexist several converters are required for the conversion causing unwanted waste of energy and ultimately not economical. Hence, hybrid SMGs play a crucial role where AC-interfaced sources and loads are connected to the AC bus whereas DC-interfaced loads and sources are connected to the DC bus, which ultimately helps in the reduction of the number of conversions stages. The interlinking converter is utilized to coordinate between AC and DC buses for the bi-directional flow of power [4]. The conventional commercial SMGs such as ferries with different architectures are still dominated by diesel generators (DG) operating under low-loading and/or overloading conditions due to the environmental changes, varying speed, and continuous operation during the whole day affecting the lifetime and the operational cost of the generator [5]. Therefore, ESS interfacing with these architectures, power management systems (PMS), and coordination between these sources have become an exceptionally essential feature for reliable and efficient operation.

The literature regarding coordination and hierarchical control for SMGs mostly relies on hybrid sources-based DC distribution systems. For instance, the study in [6] utilizes BP and DGs to share the load by operating DGs at their optimal points. Such an approach has the drawback in a way that along with load sharing, transients are also shared, which may lead to instability problems. The authors in [7] try to solve this problem by maintaining DC bus voltage constant through BPs while operating DG at a fixed point; hence, any variation in propulsion motor will be catered by BPs while during fault side at generator side, BP will supply maximum power. Further, a hierarchical control for DC SMGs with a novel inverse droop method along with frequency division is proposed in [8] such that higher and lower frequency fluctuations are carried by ultra-capacitor and BPs respectively. Another study, where a hybrid configuration dominated by DGs (2 MW) and BP (150 kWh) for a tugboat is considered in [9]. The BP is integrated at the DC bus side to keep DC bus voltage within the allowable threshold limit. The conventional approaches mostly lean on AC or DC-based architecture and their operation in islanded mode whereas coordination between SMG and grid during port stays is ignored. Further, none of these approaches considered the operation for hybrid AC/DC architecture, which is gaining popularity in retrofitting conventional AC-based ships. The only related approach for hybrid SMG is proposed in [10] where fixed-frequency operation during the voyage and conventional *PQ* control is utilized during port stays. Such an approach has a drawback that during constant frequency operation, DGs operating at a fixed point during the whole voyage result in continuous charge and discharge of BPs. Further, failure at the battery side converter will lead to instability issues at the DC bus as BP maintains the DC bus voltage. Moreover, while charging BP through shore connection conventional *PQ* control is utilized, which leads to another issue that fast charging based on constant current-constant voltage (CC-CV) charging cannot be adapted, which is recommended by the battery manufacturer [11]. The potential use of SMG for exporting power back to the grid is ignored in the study as well.

Therefore, this study proposes a modified hierarchical control structure, where multi-mode control for the operation of hybrid SMG during an islanded operation is considered. For the primary control, PMS for the interlinking converter is proposed based on fixed and varying frequency operation for power-sharing between DGs and BP. This strategy based on fixed and varying frequency under different loading conditions helps to achieve the quasi-load-leveling. Quasi load leveling is defined here as, during low and overloading operations, BP will store and supply power respectively whereas, during operation of load between the minimum and the maximum threshold limit, BP will share the least amount of power. It helps to achieve better fuel efficiency, reduction in the operational cost of DGs, and utilization of BPs. Further during long stays at the port, hierarchical control based on conventional $P-f$ and $Q-V$ droop control is adopted where secondary control is responsible for synchronization and export of power to the grid respectively. To implement an overall control strategy we have taken into consideration a hybrid-electric ferry (Happiness ferry), which sails on a river crossing of 650 m in Kaohsiung, Taiwan [12], the parameters for the case study are extracted from it. To summarize the contribution of this study:

1) The multi-mode features with adaptive PMS aid in achieving autonomous operation during the ship's islanded and grid-connected modes, there is no such scheme that exists in the literature that encompasses all these modes.
2) The hierarchical control strategy for Ship-to-X (S2X) operation is presented such that during long stays at the port power can be exported and imported to and from the grid to charge or discharge BP integrated into the ship for emergency purposes.
3) Presents an adaptive droop-based power-sharing scheme for proportional power-sharing in accordance with the state of charge (SOC) of BP.
4) A multi-mode control strategy is developed based on a bi-directional three legs DC-DC converter for its operation during the voyage and on port charging operation.

The outline of the paper is as follows. In Section II, the architecture of different types of SMGs along with the benefits of integration of ESS in SMGs are discussed. The coordination control scheme along with a hierarchical control strategy for hybrid SMG is discussed in Section III. The case study and simulation results are illustrated in Section IV. Lastly, Section V concludes the overall study.

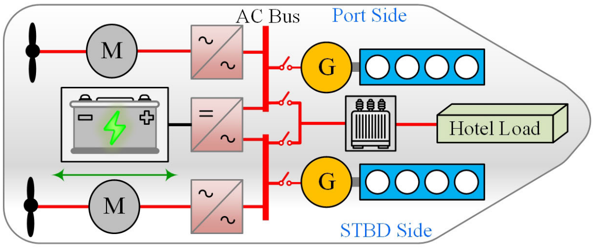
II. ARCHITECTURE AND TYPES OF SHIPBOARD MICROGRIDS WITH ENERGY STORAGE SYSTEMS

The conventional SMGs were based on mechanical propulsion with a low voltage alternating current (LVAC), i.e., 400 V (50 Hz) or 440 V (60 Hz), which are typically less than 1 kV [13]. These mechanical propulsion-based ships are highly efficient when they operate in between 80 to 100% of top speed [14] and, due to lesser conversation stages ultimately helps in lower conversion losses. With an increase in the size of the ship, the power demand increases, and hence with the similar level of voltage protection devices with high amps needs to be integrated along with the losses issues with such low voltage levels. The development of semiconductor devices (AC and DC drives) in the late 20^{th} century helped in the transition from mechanical propulsion to electric propulsion resulting in fuel-savings [15]. As the ship operates under varying load profiles due to the environmental changes that occur in the ocean and hence, prime movers are operated at their optimum points by turning on and off generators. Further, in order to cope with the highly varying load profile, ESS could be integrated into ships, which further provides several benefits such as cutting down emissions, minimizing operational cost, and improving comfort and safety.

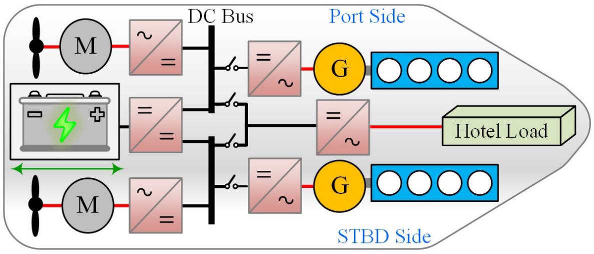
A. ARCHITECTURES OF SMG BASED ON THE DISTRIBUTION

The conventional ships were integrated with segregated-based radial AC power systems having separate generators for propulsion and service/hotel. In such a type of power system, excess power is wasted when the ship operates either under low speeding times or during idle conditions [16]. These segregated systems are then converted to an integrated power system as illustrated in Fig. 1(a), where there is a combined power system for both propulsion and service load that helps in minimizing the number of primer overs and increases the overall efficiency. Although AC distribution has benefits in a way that output of generators is AC and hence, fewer conversation stages are required. Where there are benefits of using an AC power system, there are several disadvantages such as power quality issues (harmonic distortion), stability issues, synchronization of multiple generators, control and monitoring of voltage along with frequency, reactive power compensation, bulky transformers, etc [17].

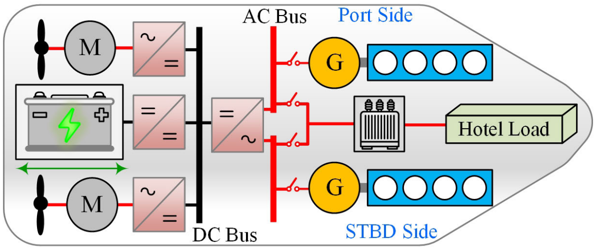
DC-based distribution illustrated in Fig. 1(b) helps in the bi-directional flow of power, integration of BPs, lack of requirement for reactive power compensation, harmonic issues, along with controlling only voltage parameters. The propulsion motor loads account for the major part of the ship's load typically between 70–80%, which helps in minimizing the rectification phase in the variable frequency drives. Two configurations are mainly adopted in DC-based SMGs, one is the multi-drive approach, and the other is distributed approach [18]. In the former structure, all the converter modules are placed in one place, similar to the AC switchboard, which leads to distribution losses. On the other hand, all the converters are placed close to respective sources or the loads in the latter category. The removal of the AC switchboard and bulky transformers helps in minimizing weight, space, and volume onboard ships. Further, RES such as fuel cell and solar panels is DC, which makes it easy to integrate with the DC power systems with a single DC-DC conversion stage.



(a) **AC-based shipboard microgrid.**



(b) **DC-based shipboard microgrid.**



(c) **Hybrid AC/DC-based shipboard microgrid.**

FIGURE 1. Architecture of shipboard microgrids.

The hybrid SMGs encompasses the benefits of both AC and DC distribution system, which are gaining popularity in terrestrial microgrids (TMGs) as well in SMGs such that AC-based sources (DGs) are interconnected with the AC bus whereas DC-based distributed energy sources are connected to the DC bus using DC-DC converters as depicted in Fig. 1(c). These two power systems are then interfaced with each other by using an interlinking converter such that active power is transmitted either from the DC bus to the AC Bus side or the vice-versa [4]. Hence, in this study, we have taken a hybrid AC/DC architecture where multiple generators and hotel load are interfaced with the AC bus and propulsion motors are integrated with the DC bus, thus eliminating the rectification stage involved in it. For a

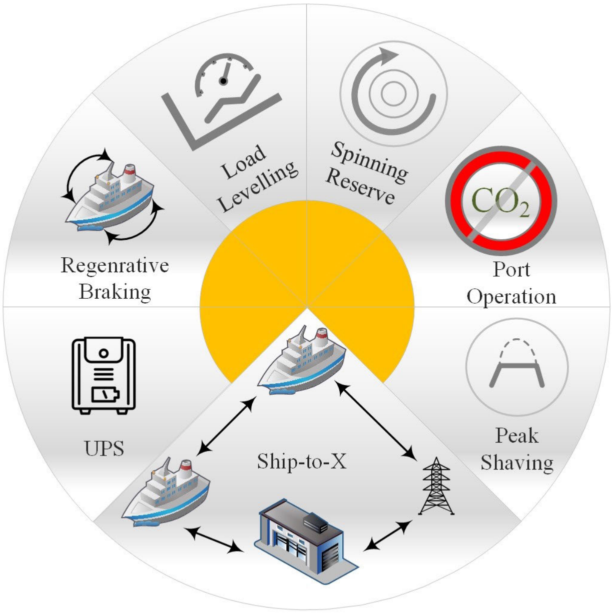


FIGURE 2. Benefits of energy storage systems in shipboard microgrids.

bi-directional flow of power, the interlinking converter is used.

B. BENEFITS OF ENERGY STORAGE SYSTEMS IN SHIPBOARD MICROGRIDS

The introduction of ESS, particularly batteries, is not new to ships as it has been widely adopted in the past for emergency purposes. On the other hand, in recent times, due to evolvement and reduction in prices of batteries, particularly the lithium-ion batteries with the chemistry of lithium iron phosphate ($LiFePO_4$), Lithium Nickel Manganese Cobalt Oxide (NMC), lithium-titanate-oxide (LTO), along with the need of cutting down emissions have urged ship owners to consider it for traction purposes as well. Moreover, other types of ESS devices such as flywheel [19] and ultra-capacitors are being considered due to the lack of the ability of the batteries to be used in high power density applications such as peaking shaving [16] and tackling with pulsating loads [20]. Further, the hybridization of these ESS devices is being considered in order to achieve higher energy density and higher power density at the same time [21], [22]. Similar to electric vehicles (passenger cars), electric ships can be categorized into HESs, plug-in hybrid electric ships (PHESs), and AESs. Among the categorization of ships, especially ferries and cargo vessels, particularly used for short sea shipping, BPs are being used as a sole source, and such ships can be categorized as AES. *Ampere Ferry* and *Ellen Ferry* are examples of such types of ships where several modules of BPs are integrated with the DC Bus. According to the Det Norske Veritas (DNV) regulations, there should be at least two battery rooms, one at the port side whereas the other at the starboard (STBD) side [23]. The main benefits for such AES are minimal local emissions, minimal noise pollution, higher efficiency, lower operational, and maintenance costs. Among the main challenges in implementing such ships at a larger scale is the lack of availability of chargers at ports, oversized battery requirements linked to the price of batteries, weight, size, and so on. Alternatively, HES and PHES equipped with ESS and conventional DGs could be utilized where the main difference between HES and PHES is the size of BP along with the ability to be charged through a shore connection.

The integration of ESS with conventional ships can bring several advantages, as shown in Fig. 2, comprising of regenerative braking, spinning reserve, peak shaving, port operation, and UPS purposes. The first benefit that can be achieved is the utilization of ESS for emergency purposes where battery bank is usually of low voltage category typically 24 V. The second benefit that can be achieved is storing excess energy generated while applying brakes, known as the regenerative braking phenomenon. During braking, electric motors turn into generation mode, and the energy is sent back and is stored in BPs. It is successfully being utilized in electric cars as brakes are frequently applied particularly in urban areas. On the other hand, in electric ships, brakes are mostly utilized close to the port or while docking. Hence, it could be only beneficial for shorter route ships. The third benefit also refers to load leveling where during low loading excessive power is stored while supplying power in overloading conditions. Another benefit that could be gained is the utilization of ESS as a spinning reserve whereupon failure of main generation source, for instance, DG, auxiliary loads and propulsion loads can be fed through ESS. Further, a charging station or shore connection is available only at a few ports. Therefore, ESS could be used to supply power to the auxiliary loads/hotel loads to minimize emissions from ports rather than utilizing auxiliary engines. There are several instances where due to pulsating loads or due to the environmental changes in the sea, peaks are observed due to which generators are oversized. ESS particularly with high power density such as flywheel and ultra-capacitors could be useful for such an application. Lastly, S2X operation can bring several benefits, particularly in remote islands that are highly integrated with RES, such as Ærø, where ESS of ships could be used to absorb or supply power to the grid, seaport, or the peer ships.

III. HIERARCHICAL CONTROL FOR HYBRID SHIPBOARD MICROGRIDS

Due to the increased use of sources such as RES and ESS in SMGs, power electronic converters play a key role in the shipboard power system along with power electronic interfaced loads such as propulsion motors. Hence, SMGs these days are more similar to TMGs; the similarities and dissimilarities between these types of microgrids are shown in Table. 1. The major difference between these microgrids is the highly dynamic load in SMGs, which is a propulsion motor that accounts for a major part of the total loading due to the reason, the control and power management of SMGs have become complex. Due to this, a hierarchical control with multi-mode features that can adjust its mode based on high varying load

TABLE 1. Comparison between shipboard and terrestrial microgrids.

	Elements	Shipboard Microgrid	Terrestrial Microgrid
Resemblance		Islanded and grid-connected operation	
		AC,DC, and hybrid architecture	
		Increased use of power electronics converters	
		Finite Inertia	
		Bi-directional power flow	
		Increased use of renewable energy sources	
		Use of ESS for peak shaving applications	
Dissimilarities	Sources	Fossil-fuel based diesel or gas with few exceptions RES (Fuel cell, PV)-based ships	RES (Wind, Solar, Fuel Cell) and Conventional fossil-fuel based power plants
	Loads	High dynamic load (Propulsion motors), pulsed loads, and service loads	Conventional loads
	Energy storage devices	High energy density devices (battery packs) with the possibility of use of high power density devices (flywheel, ultra-capacitors)	Battery packs
	Footprints	Reduction in weight and size of power system and sources is of high importance	Not of key importance

conditions is required. Since load variations, are not that frequent in TMG, the need for a multi-mode scheme is not that evident in TMG. A hierarchical control strategy is vastly being implemented in TMGs and has become a standardized solution, adapted by following the ISA-95 framework for microgrid control [24]. This sort of strategy has a benefit in the way that each control layer is independent of the other and is mainly divided into three control layers, i.e., primary, secondary, and tertiary layers.

In this study, therefore, a three-layered hierarchical control is utilized as illustrated in Fig. 3 for hybrid-SMG by considering DGs and BPs as sources. The primary layer includes power-sharing between DGs and BPs during the islanded mode of operation whereas secondary control is responsible for voltage and frequency restoration, which helps for all-electric port operation (AEPO). The secondary control is also responsible for synchronization during grid-connected operations. On the other hand, the tertiary layer is based on the charging rate schedule based on the operational time of the ferry and its long stay at the port such that during day time fast charging (1C) is performed whereas during night time slow charging (C3) is performed.

A. DIESEL GENERATOR CONTROL

The DG comprises two main parts, which are referred to as a prime mover for the diesel engine and the second is the synchronous generator. The former one can be controlled by the governor, whereas the latter is controlled by the active voltage regulator (AVR)/exciter. To regulate the active power, the governor controls the injection of fuel by measuring the shaft speed along with the comparison with the reference of angular frequency [25]. On the other hand, the AVR helps to regulate reactive power and voltage regulation. The standardized model of synchronous machine embedded in MATLAB/SIMULINK environment is utilized, where the basic block diagram for the active and reactive power control of the DG is illustrated in Fig. 3. For active power-sharing between DGs, $P-f$ droop control is utilized with 2% droop settings.

B. AC-DC CONVERTER CONTROL – MULTI-MODE CONTROL STRATEGY FOR HYBRID SHIPBOARD MICOGRIDS

To coordinate between AC and DC Bus, a bi-directional AC-DC converter is integrated in order to control the active and reactive power-sharing in a hybrid SMG comprising of synchronous generators and BPs in an islanded mode along with the grid connection during port stays. The overall control strategy is mainly divided into four modes: Mode 1 referred to as "voyage mode", which is an islanded operation of SMG that starts when the ship is in the sea/ocean. Mode 2 operates when the ship is at the port where grid connection/cold-ironing facility is not available, Mode 3 works when the ship is at the port with the facility of grid connection such that charging of BP is performed based on CC-CV charging, lastly Mode 4 refers to as ship-to-grid (S2G) or S2X, which in case of emergency, the power from BPs or in case of availability of any greener source such as fuel cell

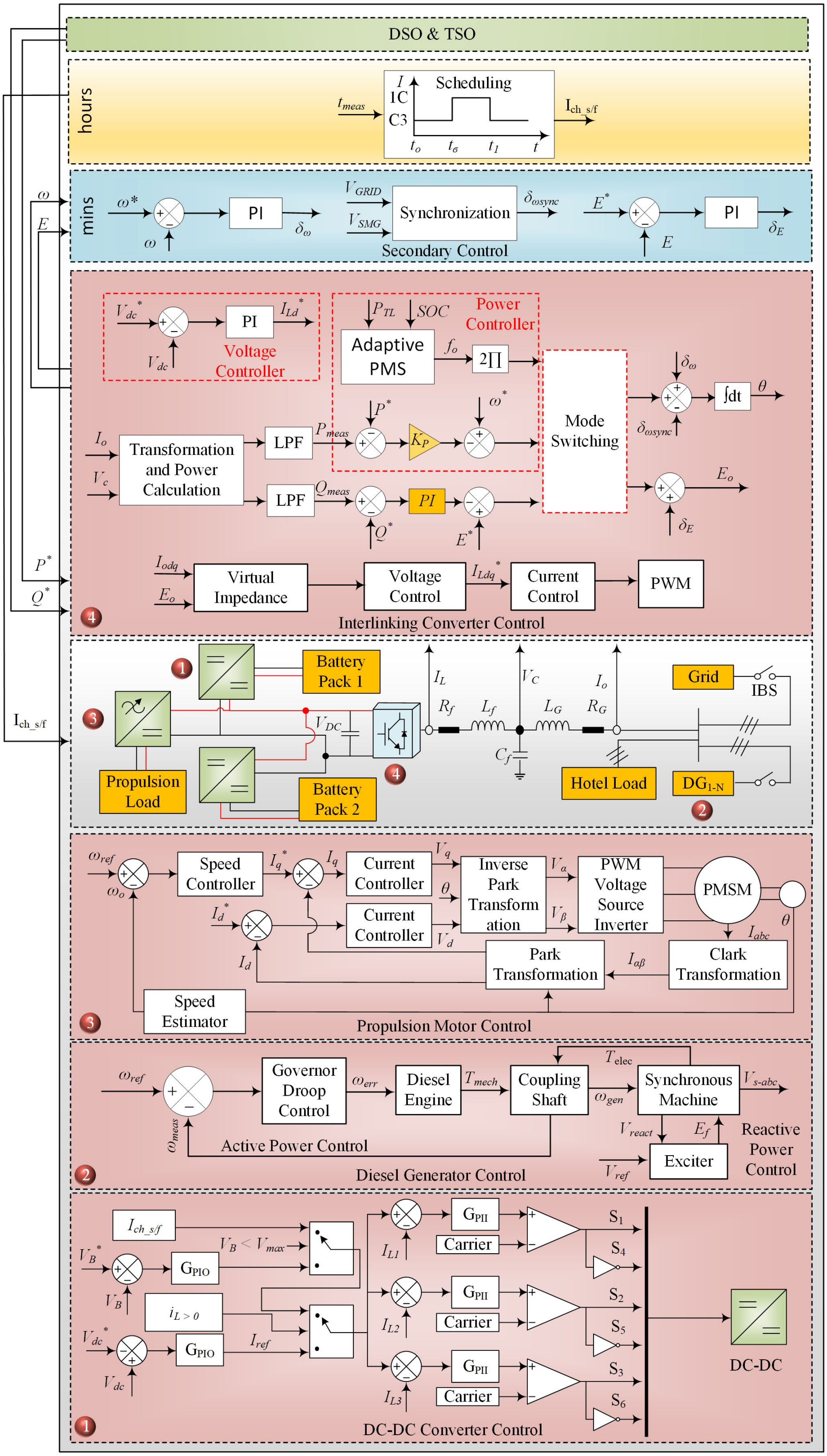


FIGURE 3. Hierarchical control for islanded and grid-connected operation of hybrid shipboard microgrid.

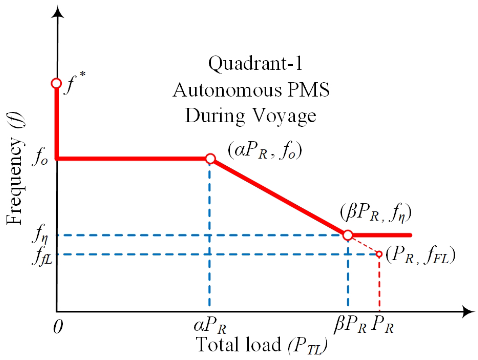


FIGURE 4. Piece-wise function to achieve quasi-load leveling.

can be utilized to support the seaport load and the grid. The controller parameters for the AC-DC converter are chosen using SISO tool in MATLAB. As the switching frequency is 10kHz, therefore, inner loop parameters are designed based on $\frac{1}{5}th$ of switching frequency whereas outer loop parameters are designed based on 600 Hz frequency while phase margin is considered to be 60 °.

1) MODE 1: VOYAGE MODE (ISLANDED OPERATION OF SMG)

Mode 1 refers to a voyage mode, as it is an islanded mode and hence, voltage and the frequency of the SMG need to be controlled. As SMG during its voyage operates under varying load profiles due to the variation in the environmental conditions and speed. Due to this, synchronous generators may operate under low loading and overloading conditions that are harmful to the generators. Specifically, the low-loading operation of DGs causes soot particles and low pressure along with an increase in pollution, which decreases the lifetime of generators. Moreover, emissions and specific fuel oil consumption (SFOC) also rely on loading on the DGs. To overcome this concern, SMGs are integrated with BP to allow engines to operate within specific optimized points to achieve improved fuel consumption and reduce emissions. Therefore, an adaptive active PMS is proposed by utilizing the piece-wise function illustrated in Fig. 4 for hybrid SMGs based on fixed and variable frequency operation. The overall algorithm based on this is designed as illustrated in Fig. 5 where it can be categorized into two possible operational modes which are defined as DG dominating mode and hybrid mode. As the manufacturers insist on operating DGs above 50% loading [26], hence, in this study minimum threshold limit (α) is set to be 50 %, and the maximum threshold limit (β) to 90 % of the rated value. The permanent permissible limits for frequency deviations according to the American Bureau of Shipping (ABS) [27] and DNV is $(\pm 5\%)$ whereas according to IEEE Std. 45.1-2017 it is $(\pm 3\%)$ [28], therefore, frequency deviation in this study is set to be $(\pm 1\%)$ (1), as shown at the bottom of the page.

The PMS is designed based on the following points:

1) If the SOC of BPs is within the maximum and minimum threshold limit, the following points need to be considered:
   a) DGs need to be operated at a value greater than the threshold limit, i.e., αP_R. Hence, if the total load (P_{TL}) falls below this threshold value, the frequency will be set to f_o, which is an average of f^* (no-load frequency) and f_{FL} (full-load frequency) as expressed in (1) where the rest of the power will be stored in the BPs. This mode operates when the ship is running at a lower speed and is referred to as a hybrid mode under low-loading operation.
   b) When the ship is running at a higher speed or during overloading conditions, which usually occurs due to the environmental changes in the sea, i.e., βP_R, DGs will operate at the fixed frequency referred to as f_η where the rest of the power will be supplied by the BPs.
   c) When the ship operates at a value greater than the minimum threshold limit and below a maximum threshold limit i.e. $\alpha P_R \leq P_{TL} \leq \beta P_R$, the ship operates in DG mode, and BP will share the least amount of power), referred to as f_{DG}.
2) Although BPs are operated between the SOC_{min} and SOC_{max} value, in case, if the SOC of BP falls below the threshold limit (SOC_{min}), our goal would be to operate at a frequency f_η such that to charge BPs up to predefined value, i.e., SOC_ζ.
3) Whereas if SOC of BPs is above the threshold limit, i.e, SOC_{max}, the ship will operate in a hybrid mode and the frequency would be equivalent to f_o.

2) MODE 2: ALL-ELECTRIC PORT OPERATION MODE (ISLANDED OPERATION OF SMG)

The integration of BPs in modernized ships can further help in minimizing emissions from the ports. The generator's onboard will be turned off as soon as the ship is berthed at the port and the auxiliary load will then be supplied by the onboard BPs. In ships, auxiliary loads are far less than the overall loading as propulsion motors account for the major

$$f_{PMS} = \begin{cases} f_o = \dfrac{f^* + f_{FL}}{2} & 0 \leq P_{TL} < \alpha P_R \\ f_{DG} = f_o + \dfrac{f_\eta - f_o}{\beta P_R - \alpha P_R}(P_{TL} - \alpha P_R) & \alpha P_R \leq P_{TL} \leq \beta P_R \\ f_\eta = f_o + \dfrac{f_{FL} - f_o}{P_R - \alpha P_R}(\beta P_R - \alpha P_R) & P_{TL} > \beta P_R \end{cases} \tag{1}$$

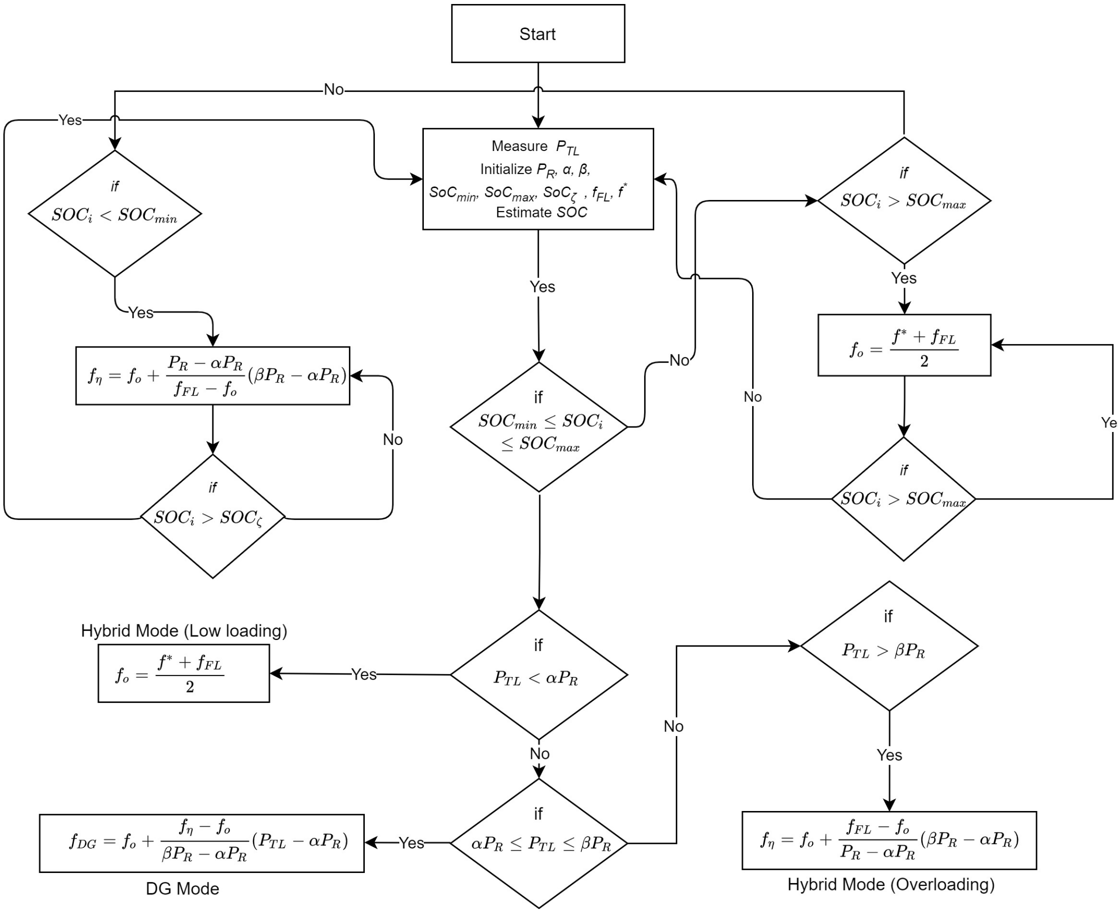


FIGURE 5. Adaptive power management system for shipboard microgrids.

part of the loading. In order to seamlessly transform from DG or hybrid mode to AEPO, a secondary loop is added bringing back the frequency and voltage to the nominal values. The secondary loop will be activated as soon as the speed of the propulsion motor reaches close to zero.

$$\delta\omega = K_{pfs}(\omega^* - \omega) + K_{ifs}\int(\omega^* - \omega)dt$$
$$\delta E = K_{pes}(E^* - E) + K_{ies}\int(E^* - E)dt \tag{2}$$

where K_{pfs}, K_{ifs}, K_{pes}, K_{ies} are the PI parameters for secondary controller whereas ω^*, E^* are the references for the angular frequency and the voltage respectively, measured angular frequency and voltages are represented by and ω, E.

3) MODE 3: CHARGING MODE (GRID-CONNECTED OPERATION OF SMG)

In the presence of cold-ironing facilities available at the shore, ship BP needs to be charged where the rectification stage along with DC-DC conversion is performed on-board also referred to as an on-board type of charger. In order to charge the BP through the shore connection based on a well-renowned charging method, i.e., CC-CV, AC-DC converter will behave as an active front end converter where the outer power loop will be replaced by the voltage loop as DC bus voltage needs to be maintained such that V_{DC}^* is compared with the V_{DC} and passed through the PI controller as shown in Fig. 3.

4) MODE 4: SHIP-TO-GRID & SHIP-TO-X (GRID-CONNECTED OPERATION OF SMG)

S2G, a technology that allows energy to be sent back to the grid from the BPs of an electric ship whereas S2X can be referred to as "ship-to-everything", which can be ship-to-seaport, ship-to-home, ship-to-grid, ship-to-building, etc. SMG will now work in grid-connected mode; therefore, the AC-DC converter will operate in conventional $P - f$ and $Q - V$ droop control. The droop control strategy can be demonstrated as follows:

$$\theta = \theta^* - K_P(P_{meas} - P_{ref})$$
$$E = E^* - (\frac{K_{QP}s + K_{QI}}{s})(Q_{meas} - Q_{ref}) \tag{3}$$

where $\theta^* = \omega t$, E^*, P_{ref}, and Q_{ref} are the phase and the voltage values at no load, references for the active and reactive power respectively, where commonly P_{ref} and Q_{ref} are set to zero. K_P, K_{QP}, and K_{QI} are the droop coefficients.

In order to deliver power back to the grid, with other peer SMGs, or import power, synchronization needs to be performed where amplitude, phase angle, and frequency of SMG are matched with the grid. To employ the synchronization process, an orthogonal product of alpha-beta components of the SMG and the grid-based methodology is adopted proposed in [29] as expressed in (4). The orthogonal product of both the voltages is passed through a PI controller and the signal is sent to the inverter, hence, adjusting the $P-f$ droop function.

$$\delta_{\omega sync} = (V_{g\beta}.V_{SMG\alpha} - V_{g\alpha}.V_{SMG\beta})(\frac{K_{psyn}s + K_{isyn}}{s}) \quad (4)$$

where K_{psyn} and K_{isyn} are the proportional and integral term for synchronization between the grid and the SMG.

On the other hand, to import or export power from the grid, the reference signals of active and reactive power (P_G^* and Q_G^*) are sent by the distribution system operator (DSO) or Transmission System Operator (TSO). Upon the availability of an energy management system in the SMG, the power can be delivered according to various factors such as excessive generation upon the availability of greener resources but in this study, it is assumed that the reference signals are set by DSO or TSO.

C. MULTI-MODE CONTROL STRATEGY FOR DC-DC BI-DIRECTIONAL CONVERTER

The two BPs are interfaced with the DC-bus using bi-directional DC-DC converting units. The conventional studies lean on equal power-sharing among different battery banks leading to the over-discharge battery with a lower SOC. In order to cope with this challenge, studies [3], [30], [31] presents an adaptive droop scheme for proportional power-sharing such that a battery with higher SOC shares the highest power whereas the least power is shared by the battery with lower SOC. To implement an adaptive droop, virtual resistance is added in the outer voltage loop where the charging and discharging coefficients are calculated using (5)–(6). The two-quadrant operation, as shown in Fig. 6 shows the expansion of the conventional droop scheme where the first quadrant indicates the discharging mode whereas the second quadrant points out the charging mode.

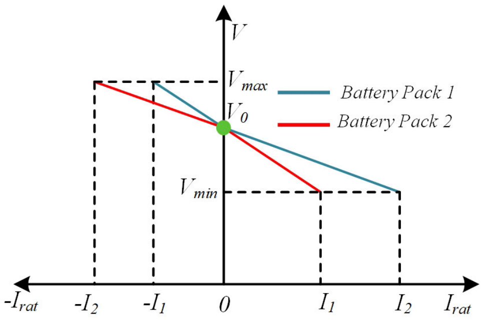


FIGURE 6. Adaptive droop charging and discharging mode.

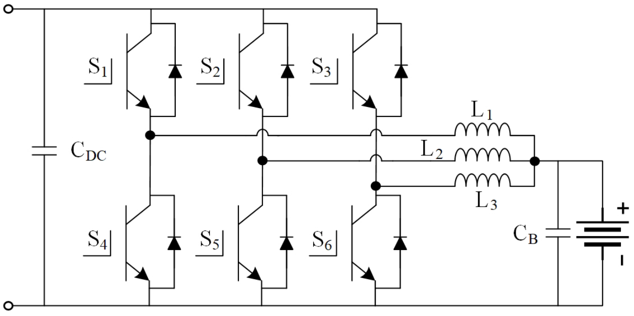


FIGURE 7. Schematic diagram of DC–DC converter.

$$R_{\mathrm{DCharg}} = R_{\mathrm{v}} \left(\Psi + \frac{SOC_{\mathrm{k}} - SOC_{\mathrm{min}}}{SOC_{\mathrm{max}} - SOC_{\mathrm{min}}} \right) \quad (5)$$

$$R_{\mathrm{DDisch}} = R_{\mathrm{v}} \left(\Omega - \frac{SOC_{\mathrm{k}} - SOC_{\mathrm{min}}}{SOC_{\mathrm{max}} - SOC_{\mathrm{min}}} \right) \quad (6)$$

where $\mathrm{k} = 1{,}2$ and virtual resistance is varied linearly from R_v to $2R_v$ such that $\psi = 1$ and $\Omega = 2$.

Conventional DC-DC converters rely on two switches for bi-directional operation. Due to an increase in power demand with a need for higher efficiency and power density, DC-DC converters with multiple legs are of much attraction. Therefore, in this study, a three legs-based DC-DC converter is utilized, which helps in sharing inductor current in three legs as illustrated in Fig. 7. The batteries onboard can be charged either through generators placed on-board or during ships port stays through shore connection. The control of the DC-DC converter is illustrated at the bottom of Fig. 3 is divided into two main modes:

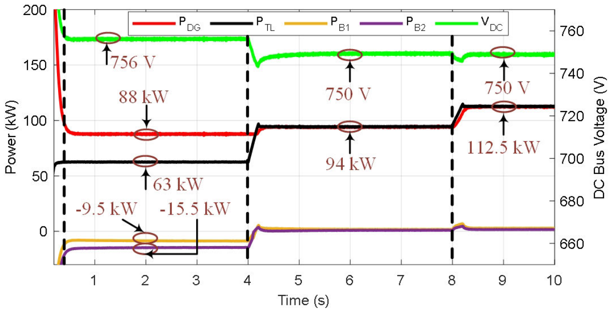
1) Dual-loop cascaded control operating during voyage mode is adopted where the outer loop is the voltage control loop whereas the inner loop is the inductor current loop. The goal for this mode of control is to supply power during overloading conditions whereas to absorb power during low-loading operation of DG. Any transients at the DC bus side by the propulsion motor will be catered by the BP.
2) The second mode refers to as charging of BPs during port stays such that during day time fast charging is performed whereas during night time slow charging is performed in order to increase the lifetime of BPs. The charging rate selection will be performed based on scheduling, and the signal will be sent by the tertiary layer to the primary layer. The switching between modes is based on inductor current, i.e., if $i_L > 0$, the charging mode starts. As, during on port stay, the power supplied by DGs will be turned off, hence inductor current signaling will help in switching between the modes.

TABLE 2. **Parameters of happiness ferry.**

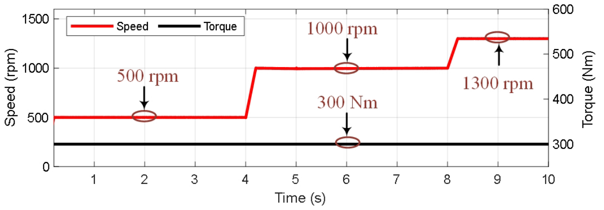
Category	Parameters	Values
Synchronous generator	Electric Power	2x88 kW
	RMS voltage	440 V
	Nominal frequency	60 Hz
Battery Packs	Nominal voltage	650 V
	Rated capacity	160 Ah
Propulsion Motor	Rated power	2x112 kW
Hotel load	Nominal power	35 kW
Voltage	DC Bus voltage	750 V
Interlinking Converter	Inner Loop	K_{pi}=13.93, K_{ii}=4875
	Outer Loop	K_{pv}=0.4586, K_{iv}=494.6
	Secondary Control	K_{pfs}=0.9, K_{ifs}=0.001
		K_{pes}=0.8, K_{ies}=0.01
		K_{psyn}=0.0005, K_{isyn}= 0.001
DC-DC Converter	Inner Loop	$K_{iv_d} = 5$; $K_{ii_d} = 10$
	Outer loop	$K_{pv_d} = 2$; $K_{iv_d} = 100$
Grid Connected Mode	Droop coefficients	$K_P = 5e-5$, $K_{QP} = 7.6e-5$, $K_{QI} = 1e-2$

D. PERMANENT MAGNET SYNCHRONOUS MOTOR CONTROL

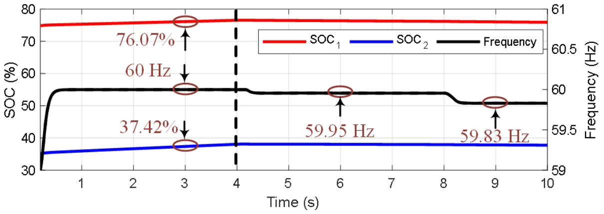
At present, AC induction motors are the most deployed motors in the world, which are being extensively utilized in the homes and industry because of their lower cost, simple and rugged construction. Whereas motors for electric ships are relatively different from conventional household motors as they are of low speed and typically are huge in terms of their ratings [32]. For the electric ship application, the permanent magnet synchronous motor (PMSM) is widely adopted due to its higher efficiency, smaller size, high power density, higher ratio of torque to current, and faster dynamic response [33]. To control the speed of PMSM, the field-oriented control method is utilized where the rotor angle and stator currents are measured to control the torque and the magnetic flux. The components d and q of stator currents obtained by the Clark and Park transformation are utilized to control the flux and the torque, the basic block diagram is illustrated in Fig. 3 where power can be calculated using (7).



(a) **Diesel generator power, total load, battery power, and voltage of DC bus.**



(b) **Speed and torque of propulsion motors.**



(c) **SOC of BP and frequency of SMG.**

FIGURE 8. **Simulation results for low-loading scenario.**

$$Power(W) = \frac{2\pi NT}{60} \tag{7}$$

where N is the rotational speed, T is the torque, which is expressed in *rpm* and *Nm* respectively. Hence either by varying the torque or the rotational speed the output power can be varied.

IV. SIMULATION RESULTS AND DISCUSSION

The case study taken into consideration in this study is the Happiness ferry as shown in Fig. 9, originally a diesel-powered ferry, which was retrofitted with a hybrid architecture comprising of two DG along with BPs. The ferry operates between Gushan pier station and Cijin on a 650m route in Kaohsiung, Taiwan. During its journey, the voyage time of the ferry is 5 minutes whereas the ferry stays at each port for 5 minutes as well. The parameters for this ferry are enlisted in Table. 2.

A. CASE 1: HYBRID OPERATION (LOW-LOADING CONDITION)

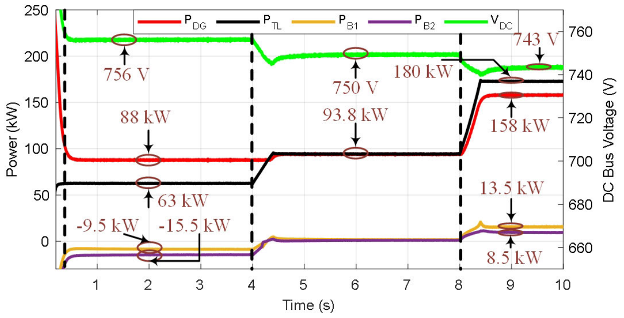
The first case study taken into consideration is when the ship is running at a slower speed. In such a low-loading condition,

FIGURE 9. A case study into consideration–happiness ferry, Kaohsiung, Taiwan.

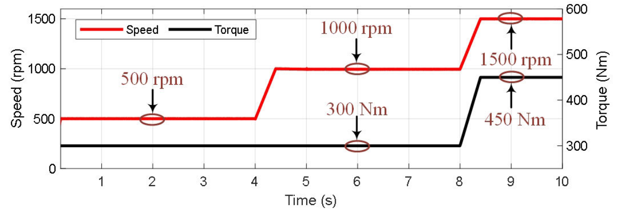
the efficiency of DG decreases and has an adverse effect on the ship's engine. In order to cope with this challenge, BP is integrated, which helps to operate DGs at their minimum threshold limit. It is done by using a fixed-frequency operation; as a result, the rest of the generated power is absorbed by the BPs as illustrated in Fig. 8. The initial SOC for BPs are considered to be $SOC_1 = 75\%$ and $SOC_2 = 35\%$. It can be seen from Fig. 8(a) that up to 4s, the total power consumed by the propulsion motor and hotel load is far less than the minimum threshold limit, i.e., 88 kW, and hence, the rest of the power is absorbed by the BPs. On the other hand, at 4s and 8s speed of the ship increases, as shown in Fig. 8(b), therefore, the total loading now falls between the minimum and maximum threshold limit. Hence, BPs now will supply the least amount of power, which increases the lifetime of BPs. Moreover, it can be inferred that the highest power is absorbed by the battery pack with the lowest SOC as shown in Fig. 8(c). In addition, due to the increase in contribution from diesel generators at 4s and 8s, frequency of the system drops.

B. CASE 2: HYBRID OPERATION (HIGH-LOADING CONDITION)

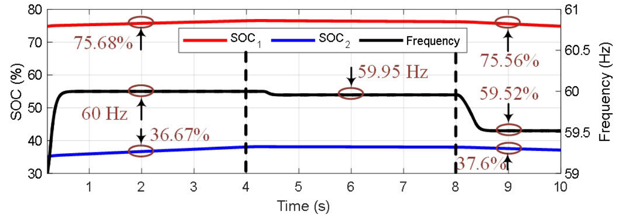
In order to verify the case study where the ship is operated under overloading conditions, ship speed along with the torque of propulsion motor is varied while keeping hotel load constant. It happens when the ship is running at a higher speed and/or because of the environmental changes in the sea. The initial SOC for BPs in this case study is considered to be $SOC_1 = 75\%$ and $SOC_2 = 35\%$. It can be seen from Fig. 10(a) that up to 4s ship is running at low speed and hence power is being absorbed by the BP. At 8s, the shipping speed starts to increase along with the variation in the torque as shown in Fig. 10(b); hence, power demand increases above the maximum threshold limit of DGs i.e., βP_R, therefore, BP will now support by supplying power. It can further be visualized that during charging of BP, SOC_2 is absorbing comparatively more power due to lower SOC. On the other hand, after 8s due to over-loading scenario, BP will support and during discharging BP with lower SOC (SOC_2) contributes the least as shown in Fig. 10(c). It can be visualized that owing to an increase in contribution from DG, frequency drops and remains within ±1%.



(a) **Diesel generator power, total load, battery power, and voltage of DC bus.**



(b) **Speed and torque of propulsion motors.**

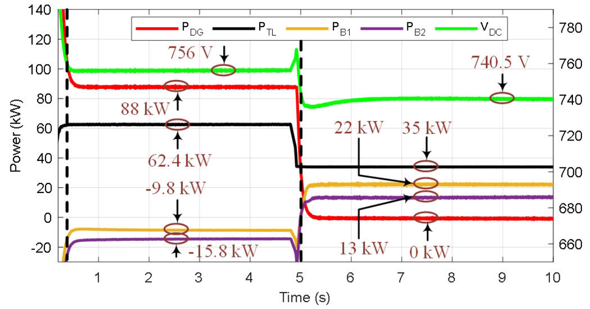


(c) **SOC of BPs and frequency of SMG.**

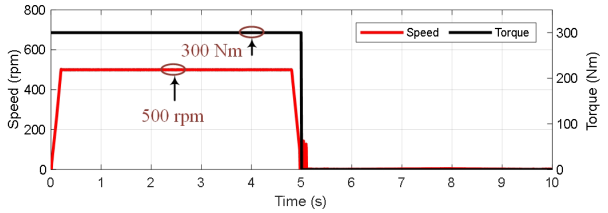
FIGURE 10. Simulation results for over-loading scenario.

C. CASE 3: ALL ELECTRIC PORT OPERATION (AEPO)

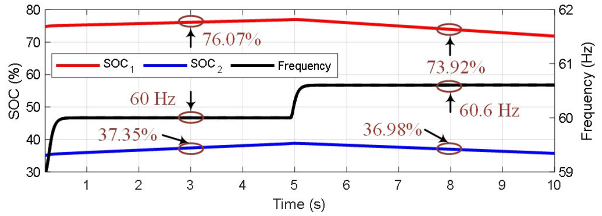
This case study illustrates the utilization of BP to power hotel load during ships stay at the port where cold-ironing facilities are unavailable. It can be seen from Fig. 11(a) that up till 5s the ship is operating in a hybrid mode. As soon as the ship reaches the port, the speed of the propulsion motor drops down and reaches close to zero as observed



(a) **Diesel generator power, total load, battery power, and voltage of DC bus.**



(b) **Speed and torque of propulsion motors.**



(c) **SOC of BPs and frequency of SMG.**

FIGURE 11. Simulation results for all-electric port operations.

from 11(b). It activates the secondary controller thus bringing the frequency back to the nominal value, hence hotel loads now are supplied by the BPs. It can further be inferred that bus voltage up to 5s remains above the nominal value indicating that battery is being charged. After 5s, bus voltage drops to 740.5 V depicting that BPs are being discharged. However, bus voltage remains within threshold limit, i.e., ±5% of nominal voltage. In addition, it can further be clarified from Fig. 11(c) that up to 5s owing to have a low-loading operation, SOC of BP is being increased whereas from 5s AEPO starts and hence, SOC of BP starts to fall. During discharging mode of BPs, SOC_1 absorbs the least power due to the highest SOC whereas in charging mode it contributes the most.

D. CASE 4: CHARGING MODE

This case study refers to charging mode where during day operation fast charging is performed due to shorter time staying at the port whereas slow charging is performed during night time where ship stays at the port for several hours. As it is an on-board kind of charger, hence, AC-DC converter control will be switched from power control mode to voltage control mode where DC bus voltage will be maintained by an AC-DC converter. The DC-DC conversion stage is then utilized in order to perform CC-CV charging. It can be verified from Fig. 12(a) that BP is being charged at a 1C rate (160A) un till battery voltage reaches the maximum voltage, which in this case is 744 V. As soon as the battery voltage reaches the maximum voltage limit, CV stage starts. Hence, the current supply continues to drop and ultimately will reach zero as soon as the battery is fully charged.

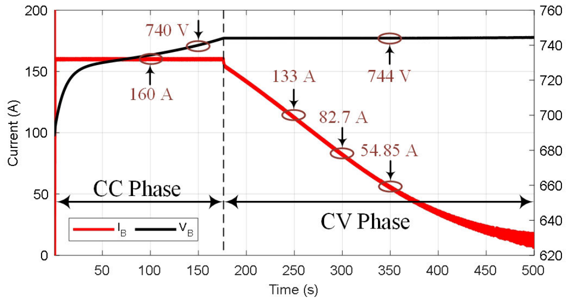
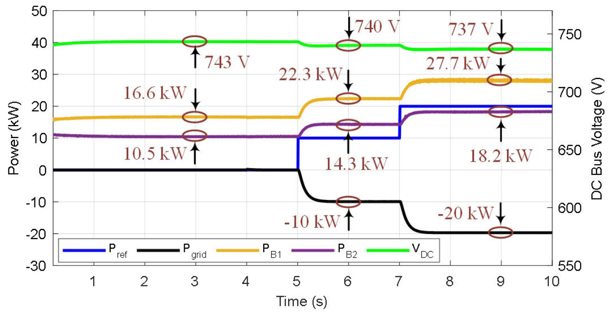
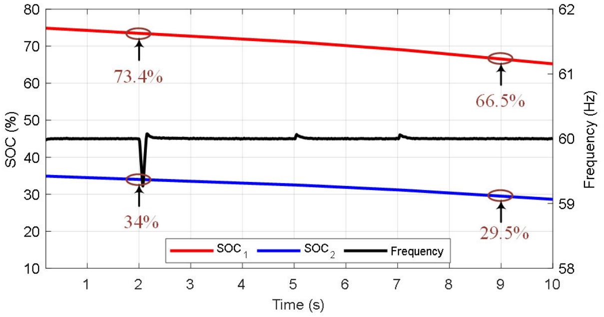


FIGURE 12. CC-CV charging during on port operation.



(a) **Power supplied and absorbed by the battery packs and grid along with voltage of the DC bus .**



(b) **SOC of battery packs and frequency of SMG .**

FIGURE 13. Simulation results for ship-to-x operation.

E. CASE 5: SHIP-TO-X

As modernized ships are equipped with BPs with several kWh ratings, hence, during emergencies, SMGs could be useful for supporting the grid upon the availability of a shore connection. Hence, the last case study illustrates when SMG is working in grid-connected mode (exporting power) during its berth-in time at the seaport. The flow of power can be controlled by the references of active and reactive power sent by the DSO or TSO. The initial SOC for BPs are considered to be $SOC_1 = 75\%$ and $SOC_2 = 35\%$. It can be visualized from

Fig. 13(a) that up to 5s, BPs of SMG are powering its hotel load such that SOC_1 with higher SOC shares the most power. Up till 5s, the demand of power from the grid is zero whereas the grid absorbs power with a step change of 10kW at 5s and 7s. In addition, bus voltage drops indicate that BPs are being discharged and remain within the minimum threshold limit, i.e., -5% of nominal voltage. To connect to the grid, synchronization has started at 2s, and frequency is brought back to the nominal value as illustrated in Fig. 13(b). Moreover, owing to having the highest SOC (SOC_1) shares the most power, therefore, drops more in comparison to SOC_2.

V. CONCLUSION

This study illustrates the operation of plug-in hybrid SMG in an islanded mode during its voyage and grid-connected modes upon its berth-in time. For an islanded mode, an adaptive active power management system is proposed to achieve quasi-load leveling. Thus during the low-loading operation of SMG, excessive power will be stored in BPs whereas, during overloading conditions, the battery pack will supply the power. On the other hand, when the loading is between the minimum and maximum threshold limit, the diesel generator will increase its contribution, a trade-off between running diesel generators at their most optimum point and utilizing a battery. By operating, diesel generators within the specified operating point will result in improving specific fuel consumption. As for short sea shipping, shore connection, or charging infrastructure is placed at one end such as to save the cost linked to the grid connection. Hence, to cope up with this challenge, the all-electric port operation is adopted at the other end to supply power to the hotel load, where generators are turned off to minimize emissions. To achieve this secondary control is responsible to bring back frequency and amplitude to the nominal values. On the other hand, during grid-connected operation, battery packs are charged where the AC-DC converter acts as an active front-end converter followed by the DC-DC stage where the tertiary layer will be responsible for feeding signal to perform slow/fast charging based on the time of day. Lastly, a hierarchical control-based approach is used in order to import or export power to and from the grid or support seaport load referred to in this study as ship-to-X, which can be utilized during emergency purposes.

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MUHAMMAD UMAIR MUTARRAF (Member, IEEE) received the B.S. degree in electrical engineering from the University of Engineering and Technology, Lahore, Pakistan, in 2013, and the M.Eng. degree in control theory and control engineering from Xidian University, China, in 2017. He is currently pursuing the Ph.D. degree entitled "Coordinated control and management of multiple electric ships forming seaport microgrids," with the Department of Energy Technology, Aalborg University, Denmark. His research interests include power electronics, control and integration of energy storage systems in AC and DC, hybrid shipboard and seaport microgrids, electric vehicles, and their charging infrastructure.

YAJUAN GUAN (Member, IEEE) received the B.S. and M.S. degrees in electrical engineering from Yanshan University, Qinhuangdao, China, in 2007 and 2010, respectively, and the Ph.D. degree in power electronics from Aalborg University (AAU), Aalborg, Denmark, in 2016.

From 2010 to 2012, she was an Assistant Professor with the Institute of Electrical Engineering (IEE), Chinese Academy of Sciences (CAS), where she was a Lecturer, in 2013. From 2016 to 2018, she was a Postdoctoral Fellow with AAU, where she is currently an Assistant Professor as part of the Denmark Center for Research on Microgrids. Her research interests include microgrids, distributed generation systems, power converters for renewable energy generation systems, and energy internet.

YACINE TERRICHE received the B.S. degree in electrical engineering from the University of Science and Technology, Constantine, Algeria, in 2011, the M.S. degree in electrical engineering from the University of Constantine 1, Constantine, and the Ph.D. degree in electrical engineering from Aalborg University, Aalborg, Denmark, in 2020.

During his Ph.D. degree, he has been working as a Research Assistant with the National Kaohsiung University of Science and Technology, Kaohsiung, Taiwan, from December 2019 to September 2020. Since November 2020, he has been working a Research Assistant with Aalborg University. His research interests include power electronics modeling and control, signal processing, power quality issues, microgrids, cyber security, active and passive power filters, static VAR compensators, and maritime microgrids.

CHUN-LIEN SU (Senior Member, IEEE) received the Diploma degree in electrical engineering from the National Kaohsiung University of Science and Technology (NKUST), Taiwan, in 1992, and the M.S. and Ph.D. degrees in electrical engineering from the National Sun Yat-Sen University, Taiwan, in 1997 and 2001, respectively. In 2002 and 2006, he was an Assistant Professor and an Associate Professor with the Department of Marine Engineering, National Kaohsiung Marine University, Taiwan, respectively. From 2012 to 2017, he was a Full Professor and the Director of the Energy and Control Research Center. From August 2017 to January 2018, he was a Visiting Professor at the Department of Energy Technology, Aalborg University, Denmark. He was the Director of the Maritime Training Center, NKUST, from February 2018 to July 2020. Since August 2020, he has been a Professor with the Department of Electrical Engineering, NKUST, and the Director of the Center for Electrical Power and Energy. His research interests include power systems analysis and computing, power quality, maritime microgrids, and offshore energy, recently specially focused on electrical infrastructure for offshore wind farms and maritime microgrids for electrical ships, vessels, ferries, and seaports. He received the Best Paper Prize of the Industrial and Commercial Power Systems Conference at IEEE-IAS, from 2012 to 2013, and the Best Paper Award of the IEEE International Conference on Smart Grid and Clean Energy Technologies, in 2018. He was a Guest Editor for the Special Issue on Next Generation Intelligent Maritime Grids of the IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS, in 2017, and the Special Issue on Power Quality and Protection in Renewable Energy Systems and Microgrids of *IET Renewable Power Generation*, in 2019.

MASHOOD NASIR received the B.S. degree from UET, in 2009, the M.S. degree from UMT, in 2011, and the Ph.D. degree in electrical engineering from LUMS, Pakistan, in 2018. From 2018 to 2019, he served as an Assistant Professor at LUMS. Since 2019, he has been working as a Postdoctoral Research Fellow with Aalborg University, Denmark. His research interests mainly include but not limited to power electronics, rural electrification, grid integration of alternate energy resources, electrochemical energy conversion systems, AC/DC/hybrid microgrids, and innovative teaching and learning pedagogies.

JUAN C. VASQUEZ (Senior Member, IEEE) received the B.S. degree in electronics engineering from the Autonomous University of Manizales, Manizales, Colombia, in 2004, and the Ph.D. degree in automatic control, robotics, and computer vision from BarcelonaTech (UPC), Spain, in 2009. He was with the Autonomous University of Manizales working as a Teaching Assistant and the Technical University of Catalonia as a Post-doctoral Assistant, in 2005 and 2008, respectively. He was an Assistant Professor and an Associate Professor with the Department of Energy Technology, Aalborg University, Denmark, in 2011 and 2014, respectively. In 2019, he became a Full Professor and is currently the Vice Program Leader of the Microgrids Research Program and the Co-Director of the Center for Research on Microgrids. He was a Visiting Scholar at the Center of Power Electronics Systems (CPES), Virginia Tech, and a Visiting Professor at Ritsumeikan University, Japan. His current research interests include operation, advanced hierarchical and cooperative control, optimization, and energy management applied to distributed generation in AC/DC microgrids, maritime microgrids, advanced metering infrastructures, and integration of the Internet of Things and energy internet into the smart grid. He is an Associate Editor of *IET Power Electronics* and a Guest Editor for the Special Issue on Energy Internet of the IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS.

JOSEP M. GUERRERO (Fellow, IEEE) received the B.S. degree in telecommunications engineering, the M.S. degree in electronics engineering, and the Ph.D. degree in power electronics from the Technical University of Catalonia, Barcelona, in 1997, 2000, and 2003, respectively.

Since 2011, he has been a Full Professor with the Department of Energy Technology, Aalborg University, Denmark, where he is responsible for the Microgrid Research Program. He has been the Chair Professor with Shandong University, since 2014, a Distinguished Guest Professor with Hunan University, since 2015, a Visiting Professor Fellow with Aston University, U.K., since 2016, and a Guest Professor with the Nanjing University of Posts and Telecommunications. In 2019, he became a Villum Investigator. He has published more than 500 journal articles in the fields of microgrids and renewable energy systems, which are cited more than 30,000 times. His research interests include oriented to different microgrid aspects, including power electronics, distributed energy-storage systems, hierarchical and cooperative control, energy management systems, smart metering, and the Internet of Things for AC/DC microgrid clusters and islanded minigrids, recently specially focused on maritime microgrids for electrical ships, vessels, ferries, and seaports. In 2015, he was elevated as a fellow of IEEE for his contributions on "Distributed power systems and microgrids." He received the Best Paper Award of the IEEE TRANSACTIONS ON ENERGY CONVERSION, from 2014 to 2015, and the Best Paper Prize of IEEE-PES, in 2015, and the Best Paper Award of the *Journal of Power Electronics*, in 2016. For five consecutive years, from 2014 to 2018, he was awarded by Clarivate Analytics (former Thomson Reuters) as the Highly Cited Researcher. He is an associate editor for a number of IEEE TRANSACTIONS.

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