Load Frequency-Based Power Management for Shipboard DC Hybrid Power Systems

Kiyoune Kwon
Digital Technology Research Center
Korea Shipbuilding &
Offshore Engineering
Bundang, Gyeonggi-do, South Korea
kiyoune.kwon@ksoe.co.kr

Daeseong Park
Marine Technology Centre
Norwegian University
of Science and Technology
Trondheim, Norway
daeseong.park@ntnu.no

Mehdi Karbalaye Zadeh
Marine Technology Centre
Norwegian University
of Science and Technology
Trondheim, Norway
mehdi.zadeh@ntnu.no

***Abstract*—The development of marine integrated power systems has enabled all-electric ship, with electric propulsion systems to be powered from diesel-generators. In addition, vessels with DC hybrid power sources such as fuel cell, super-capacitor, and battery have been emerging in recent decades. Despite several studies related to hybrid-electric vessels, the integration of hybrid power systems and its application for the marine industry still requires additional research tasks since marine power concepts have unique features, which are different from well-known hybrid vehicle concepts in respect of the number of generators & size, system response, and load profile characteristic. Especially, efficient power management in terms of load sharing among different hybrid power sources is one of the critical issues in the marine hybrid system. In this paper, the load frequency-based approach is proposed for power management and load sharing in DC hybrid electric ships. The main idea is that each power source has distinctiveness with respect to response time. By the application of several low-pass filters, an acceptable range of load frequency for each power source can be classified and distributed to each power controller. The integrated modeling & simulation of the DC hybrid powered vessel is developed to verify the proposed method. The simulation test is implemented as a feasibility study of the proposed load-sharing model for marine applications. As a result, the load frequency-based power management provides an effective load distribution scheme in terms of charging/discharging intervention of hybrid systems, and it is able to protect the generator from the sudden load variation which leads to tears & wears in mechanical systems as well as poor quality of power in electrical systems.**

***Index Terms*—Electric Ship, Hybrid Power System, DC Microgrid, Load Sharing, Power Management System**

I. Introduction

The development of marine integrated power systems has enabled all-electric ships (AES), with electric propulsion systems to be powered from engine-generators. In addition, vessels with DC hybrid power sources such as fuel cell, super-capacitor (SC) and battery have been introduced, and relevant researches have been emerging in recent decades.

The DC microgrid is advantageous for the grid integration of DC hybrid resources and dispersed power electronics-based loads. Several challenges in AC power systems, such as the need of synchronizing generation units, reactive power flow, inrush currents of transformers, harmonic currents, and three-phase unbalances [1] expedite researches for DC power systems.

The future of marine vessels depends on environmental regulation and fuel efficiency. To satisfy such requirements, it is indispensable to develop vessels with high-efficiency, in order to reduce not only greenhouse gas (GHG) emission but also fuel consumption. It is the reason that the AES with hybrid power system (HPS) are gradually adopted in the market, e.g. *Viking Lady* in 2009, both *Edda Ferd* and *Dyna Star* in 2013, *MF Ampere* in 2015, and *E-ferry Ellen* in 2019.

The use of energy storage system (ESS) enables flexible power generation in terms of an optimal loading condition of diesel gen-sets. For example, an ESS is charged while gen-sets are running in low loading condition, on the contrary, a sudden or a heavy load variation is responded by an ESS, which allows gen-sets to operate under the optimal specific fuel oil consumption (SFOC). It is so-called the load levelling/peak shaving strategy. Although the use of ESS can be beneficial for overall efficiency and adds to power redundancy and flexibility, the control of the ESS and the generator is critical to achieving optimal power generation with reduced fuel consumption and emission [2].

Despite several studies related to hybrid-electric vessels, the integration of the hybrid power system and its application for the marine industry still require additional researches since marine power concepts have unique features [3], which are different from well-known hybrid vehicle concepts in respect of the number of generators & size, system response, and load profile characteristic. Especially, efficient power management in terms of load sharing among different hybrid power sources is one of the critical issues in the marine hybrid system.

Therefore, in this paper, the load frequency-based approach is proposed for power management and load sharing in DC hybrid electric ships. The main idea is that each power source can be distinguished by the discharging/generating response time. By the application of low-pass filters, an acceptable range of load frequency for each power source can be classified and distributed to each power controller. The integrated modeling & simulation of the DC hybrid powered vessel is developed to verify the proposed method. A simulation test is implemented as a feasibility study of the proposed load-sharing model for marine applications.

II. Modelling of DC Hybrid Power System

A. System Schematic

The main objective of the HPS simulation in this paper is to verify the load frequency-based power management scheme. Electrical and mechanical models, e.g. diesel engine, generator and power converters, are developed by using Simulink/Simscape Electrical platform. Electrical load equipment, e.g. electrical-driven propulsion system, deck machinery, and hotel load, is represented by a 3-phase dynamic load which connected to DC grid through inverters. The total load and reference power of each power source are distributed by the load sharing module.

Hybrid power sources consist of two diesel-generators, a Li-ion battery, and a SC. A generator is connected to a diesel engine with speed governor, a voltage exciter with field voltage V_{fd} regulator and a three-phase rectifier. DC power sources, a battery, and a SC, are connected to bidirectional DC/DC converters to operate as both charging and discharging mode. The single line diagram of the hybrid power vessel is depicted in Fig. 1.

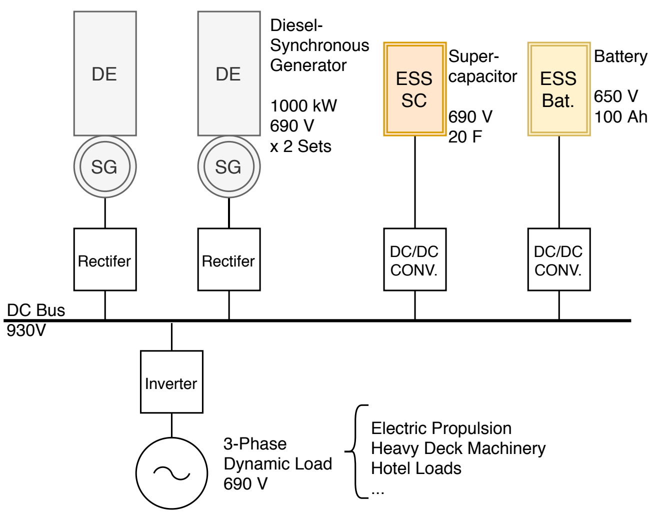


Fig. 1: Single line diagram of the hybrid power vessel

B. Component Modelling

1) Diesel Engine: For the most prime mover of ship generator is a diesel engine. In AC system, the engine speed should be matched with AC generator frequency. In DC system, however, the engine is able to operate at various, optimal speed with low SFOC. In this paper, the engine is modelled as a first order, delay function [4] between fuel injection $Y(s)$ and engine torque $T_m(s)$. In detail, a physical model of the engine can be expressed as:

$$T_m(s) = e^{-\tau s}\frac{K_y Y(s)}{1+\tau_c s} \tag{1}$$

$$\tau_c \approx \frac{0.9\ [rad]}{2\pi n_m\ [rps]}, \quad \tau \approx \frac{1}{2Nn_m\ [rps]}$$

where K_y is the fuel-torque constant index, τ_c is the time delay from cylinder firings to torque generation and τ is the time delay corresponding half period of consecutive cylinder firing. n_m is engine rotational speed in $[rps]$ and N_{cyl} is the number of cylinders.

The equation of motion of engine-generator model and its Laplace transform in per-unit $[pu]$ are derived as:

$$J_{eq}\frac{dw_m}{dt} = T_m - T_e - w_m C_r \tag{2}$$

$$w_{m,pu} = \frac{T_{m,pu} - T_{e,pu} - w_{m,pu}C_r}{2Hs} \tag{3}$$

$$(H = \frac{J_{eq}w_{base}^2}{2P_{base}} = \frac{J_{eq}w_{base}}{2T_{base}})$$

where J_{eq} is the equivalent inertia of the rotating shaft part of engine-generator system, C_r is the rotational damping coefficient and H is the time constant of equivalent inertia.

From Eq. (2), the engine speed w_m can be calculated by applying the above transfer function.

2) Generator-Rectifier: Synchronous generators are related with two controllers: one is a speed governor to adjust the frequency of AC generation and the other is a voltage exciter to regulate the field voltage. The Simscape electrical library provides a synchronous machine with dynamic model which is presented by the IEEE standard 1110-2002 [5]. The model considers the dynamics of the stator, field, and damper windings.

A rectifier is the device that converts AC to pulsating DC. a pulsating DC voltage has ripples that should be removed by using a capacitor. A full bridge diode rectifier is selected since of its low power losses with simple topology.

As considering a voltage drop due to the commutation, an output DC voltage of the rectifier is expressed as:

$$V_{DC} = \frac{3}{\pi}\sqrt{2}V_{LL,rms} - \frac{3}{\pi}\omega L_s I_d \tag{4}$$

where L_s is commutation inductance, and I_d is the DC current.

Sizing a capacitor depends on the required level of voltage ripple and a hold-up time. ABS [6] recommends maximum 10 % DC voltage ripple in terms of power quality and safety. With the voltage ripple, the capacitor sizing is calculated by using hold-up time of power converter [7]. This method is to sustain rating power within the hold-up time, and the equation is derived as:

$$W = \frac{1}{2}C(V_{max}^2 - V_{min}^2) = t_{\text{hold-up}} \cdot P \tag{5}$$

where $t_{hold-up}$ is the one-sixth cycle ($\pi/3$) of $60Hz$ 3-phase diode rectifier.

3) Bidirectional DC/DC Converter: For charging/discharging of battery and SC, a bidirectional DC/DC converter is necessary to convert voltage level from the lower DC source level to higher DC grid. There are two main topologies: non-isolated and isolated type by transformers. In actual applications, an isolated type is used in terms of large convert ratio, protection and safety issue. However, a

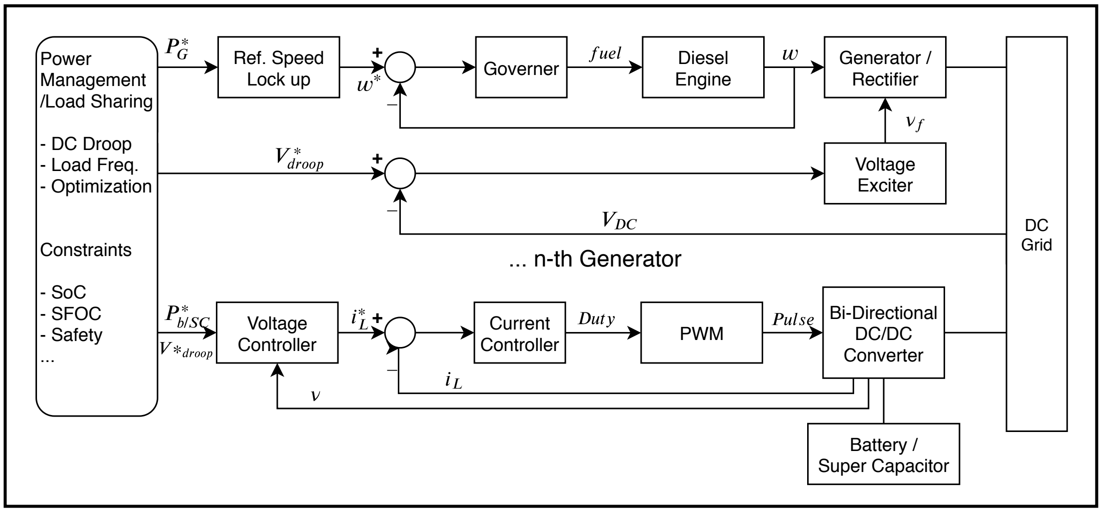


Fig. 2: Control block diagram overview of DC hybrid powered vessel

non-isolated type is still applicable in this simulation since of simpler topology, cheaper and lower loss than an isolated type [8].

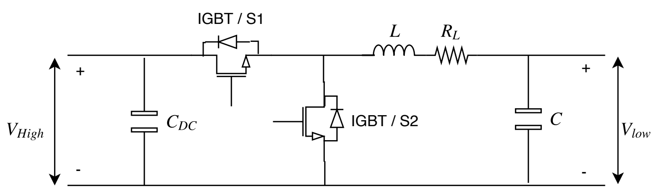


Fig. 3: Bidirectional DC/DC buck boost converter

A bidirectional buck-boost converter, as depicted in Fig. 3, is designed to control voltage and current between the high voltage side and the low voltage side. Two switching devices (IGBT) enables two operation modes depending on the direction of the power flow.

The buck mode is used in the charging mode with voltage step-down, and the boost mode is used in the discharging mode with voltage step-up. Duty ratio D, which is defined as the ratio of switching time period (T_{on}/T_{switch}), means the voltage converting ratio, and it is derived in two ways depending on buck/boost mode as:

$$\frac{V_{DC}}{V_{Bat}} = \frac{1}{1-D} \quad (Boost), \qquad \frac{V_{Bat}}{V_{DC}} = D \quad (Buck) \tag{6}$$

According to the technical report [9] from the battery supplier, the battery ripple voltage is recommended as less than 0.5% of the normal float charge voltage, and the current ripple is less than 5% of rated Ampere-hour. This mitigates battery heating and aging effects. Chao et al. [10] proposed to calculate proper impedance and capacitor of the converter by voltage and current ripple, which are formulated as:

$$L = \frac{V_{Bat}}{\Delta I_L}(1-D)T_s \tag{7}$$

$$C = \frac{\Delta Q}{\Delta V_{Bat}} = \frac{\Delta I_L T_s}{8\Delta V_{Bat}} \tag{8}$$

4) Battery and Super Capacitor: Omar et. al [11] suggested a Li-ion battery model in terms of dynamic charge/discharge operation which is provided as the Simscape electrical library. A battery sizing is not an interest in this paper. A battery with 65kWh capacity is enough to implement the proposed simulation.

A super capacitor is embodied by a basic capacitance model, and a capacity sizing is determined by the same manner of the main DC grid capacitor in Eq. (II-B2), with a longer hold-up time than the AC generator-rectifier case.

C. Control Structure

The power management system (PMS) is a crucial part of the automation and power systems on marine vessels [12]. The purpose of the PMS is to assure reliable electrical power supply to the various consumers [13].

The overall control structure of the HPS model is depicted in Fig. 2. It is partially including the function of PMS as critical constraints. The first objective of the control system is to supply required load in DC grid by distributing the reference power of each source (P^*), and the second is to regulate the DC grid voltage level within the safe voltage ripple range. PI-controllers are adopted to handle errors between the reference and measured states. Controller parameters such as PI gains are adequately tuned from the simulation test and bode plot with gain & phase margin check.

In the diesel-generator control module, engine governor controls the speed in accordance with the optimal power-speed curve in terms of SFOC, which leads optimal speed lock-up for less fuel consumption. Voltage exciter generates the field voltage V_f and regulates DC grid voltage V_{DC} by

PI controller with the voltage error between the reference and the measured value in DC grid.

In the battery/SC control module, the DC/DC converter controller regulates the voltage and current to the DC grid by manipulating PWM switching signals D in accordance with voltage and current errors. The inner current control loop (Fig. 4) is employed to regulate the current of dc-dc converter, and the voltage control loop (Fig. 5) regulates DC bus voltage. A current control loop can be constructed using the simplification in which Ls, R_L elements and the current loop can be simplified as a first-order delay [14]. With DC voltage droop, the voltage controller provides the reference current of inductor i_L^* to the inner control loop.

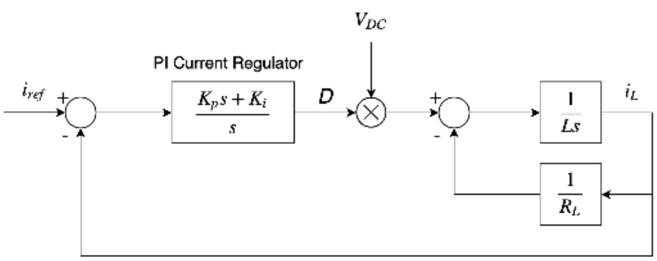


Fig. 4: Current control block diagram of DC/DC converter

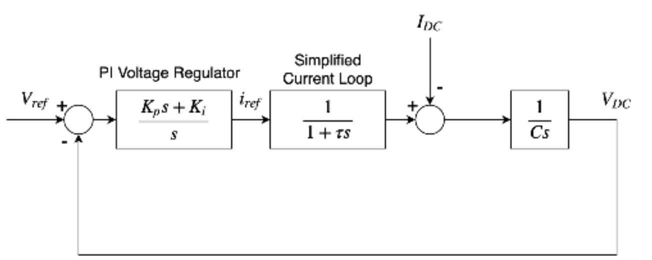


Fig. 5: Voltage control block diagram of DC/DC converter

III. LOAD FREQUENCY-BASED POWER MANAGEMENT

In DC system, a load sharing of multiple diesel-generators can be achieved by the DC droop control. Each generator has own droop characteristic which enables a load sharing among parallel generators according to a predefined droop ratio [15].

However, hybrid sources have a distinctive feature from the diesel-generator in terms of power generating/discharging response time, i.e. load frequency. For instance, SC and battery have faster discharging time than generators. It means that the conventional DC droop strategy is not appropriate to control the hybrid system. Instead, the load frequency-based power distribution is considered in order to fully exploit the capability of the different ESS units while ensuring compliance with their power and energy limits [16].

A. DC Voltage-Power Droop

Among several types of DC droop method, the voltage-power V/P droop control is adopted to control two diesel-generators with voltage exciters. The Droop parameters consist of droop slope δ_k and Y-intercept of reference voltage $V_{0,k}$. The droop slope can be calculated using defined values of minimum and maximum voltage and rated power of the generator. The linear DC droop configuration for two generators can be implemented as the matrix form:

$$\underbrace{\begin{bmatrix} \delta_{G1} & -\delta_{G2} \\ 1 & 1 \end{bmatrix}}_{\mathbf{A}} \underbrace{\begin{bmatrix} P_{G1,ref} \\ P_{G2,ref} \end{bmatrix}}_{\mathbf{x}} = \underbrace{\begin{bmatrix} V_{0,G1} - V_{0,G2} \\ P_{total} \end{bmatrix}}_{\mathbf{B}} \tag{9}$$
$$\mathbf{Ax} = \mathbf{B} \quad \Rightarrow \quad \mathbf{x} = \mathbf{A}^{-1}\mathbf{B}$$

From (9), the reference power $P_{k,ref}$ is distributed to each generator, and the reference voltage $V_{k,ref}$ of DC grid is derived as:

$$V_{ref,k} = V_{0,k} - \delta_k \cdot P_{k,ref} \tag{10}$$

In this simulation, a 4% voltage droop slope with a max $1020V$ is used for both generators, which means a equivalent load sharing. Reference voltages of hybrid sources also follows the voltage level from the generator droop since the voltage exciter is the main voltage controller except for stand-alone operations of hybrid sources. It is assumed that the SC or the battery does not operate alone in this paper.

B. Load Frequency-Based Power Distribution

The proposed method is configured by a cascade of low-pass filters, as depicted in Fig. 6. A load of the main DC grid passes through two low-pass filters which are related to an allowable load frequency range for each energy source.

The first filter ($T_l = 8$ sec) has a long period which is adaptable for the generator. The second filter with mid-period ($T_l = 1$ sec) is designed for the battery. After subtraction from the first filter load, only the mid-frequency range is left. By eliminating the first and the second load from the total load, the remained load frequency is covered by the SC with the fastest but shortest duration response.

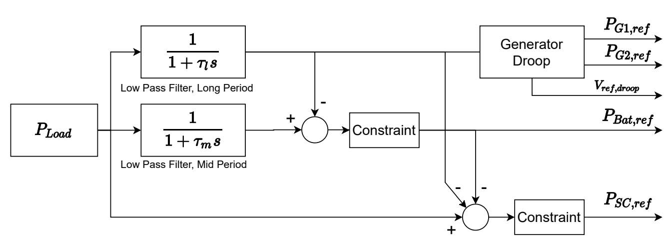


Fig. 6: Load sharing block diagram based on the frequency based filters

C. Load Constraints

There are several load constraints related to safe operation and the protection of electrical equipment. In case of battery, the protection circuit limits the peak voltage during charge and prevents the voltage from dropping too low on discharge, which is specified in C-rate. In addition, the state of charge (SoC) should remain the moderate range neither too high nor

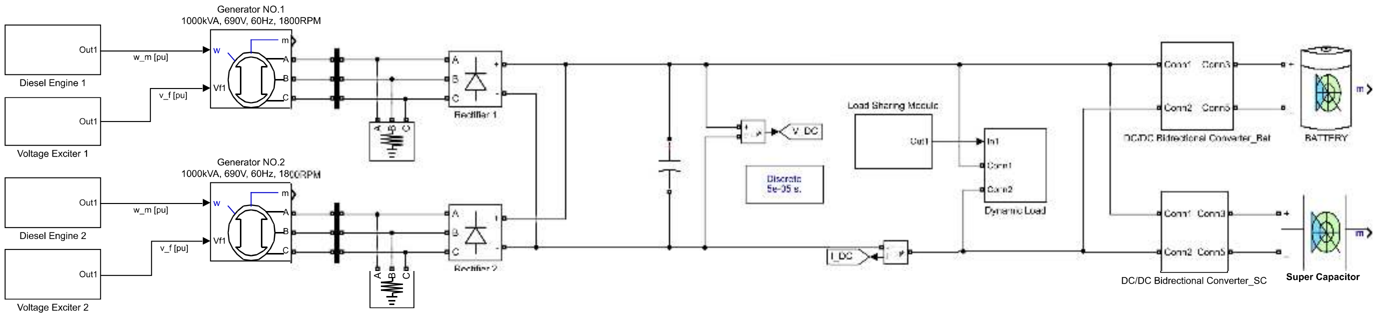


Fig. 7: Modeling layout of DC hybrid powered vessel

too low, to mitigate the aging degradation. For example in this simulation, the state of below 20% SoC only permits charging mode and the state of above 80% SoC only allows discharging mode to protect battery. SC has a similar concept but fewer constraints than battery, thus it can handle rapid power fluctuations.

IV. Simulation & Result

The main objective of the simulation is to verify the load frequency-based power management in terms of an effective load distribution for a marine application. The DC hybrid powered vessel modeling and control is integrated in the Simulink platform as shown in Fig. 7.

A. Ship Load Profile

The load profile mainly depends on both weather conditions and operating modes. The operating mode includes standby, transit, anchor handling, dredging, bollard pulling and towing mode which are combined with dynamic positioning (DP) and/or heavy machinery.

The ship load profile of the OSV *Olympic Hera* [17], which contains 60 days of actual voyage data, is reconstructed over 1000 seconds with scale-down from 10MW to 2MW because of simulation constraints. The simulation profile shows representative cases from low to high stable/transient load. The HPS simulation is conducted with the integrated modeling & control and the load profile. In Fig. 8, the red dot line is the reconstructed load profile of the vessel and the blue line is the total power generation from each source as a result of the HPS simulation.

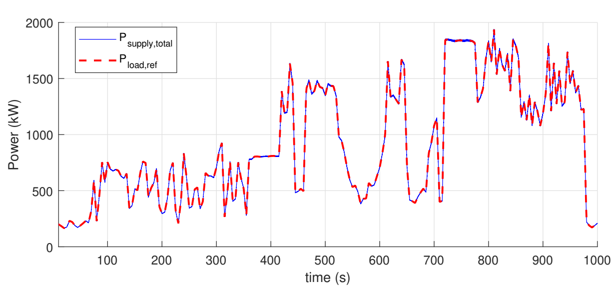
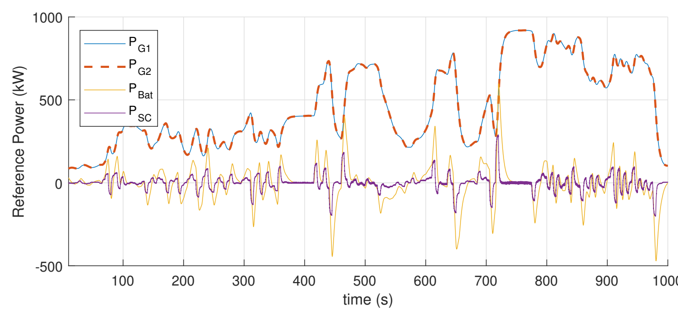


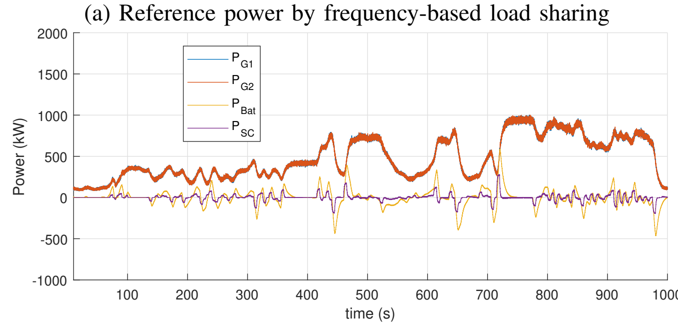
Fig. 8: Simulation reference load profile (Red dot), total power generation result (Blue)

B. Power Distribution of HPS

The load sharing and the power measurement results of each source are indicated as Fig. 9. From a comparison of both results, it is observed that each power source is successfully controlled by each control scheme as following the reference power. As observing the load sharing trend, the SC shows the fastest intervention against sudden load variation, and the next is the battery with larger capacity than the SC. Both offers marginal time for diesel-generators to operate as gradual power increase or slow reduction with less fuel consumption. Two generators reveals the slowest but stable power generations with an equal load sharing along the predefined DC droop lines.



(a) Reference power by frequency-based load sharing



(b) Power generation measurements of each source

Fig. 9: Load sharing & Power measurement results

C. Voltage & State of Charge Measurement

As shown in Fig. 10, voltage ripple and fluctuation in DC grid is within the $\pm 6\%$ from $930V$ reference voltage. From the result, the capacitor in DC grid and the DC droop control by the voltage exciter is designed to satisfy the recommended voltage tolerance $\pm 10\%$ by the ABS guideline [6].

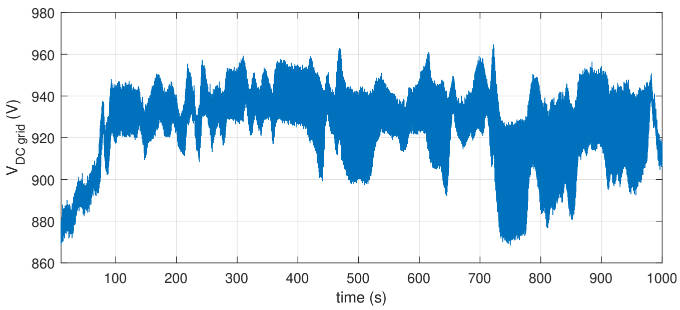


Fig. 10: DC-grid voltage measurement

The SoC of SC/battery displays charge/discharge status and rates. As shown in Fig. 11, the SC and the battery repeat charging and discharging without falling below a low limit because both the load frequency-based power management and load sharing constraints adequately controls the HPS as intended. However, load increasing and decreasing tendency are not always matching as desired, thus further energy management scheme is required for flawless SoC control, which will be discussed in the conclusion.

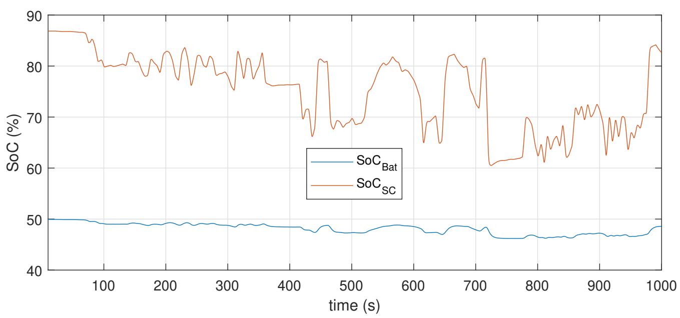


Fig. 11: State of charge, super capacitor and battery

V. Conclusion

In this paper, the integrated modeling & simulation of DC hybrid vessel is conducted to verify the load frequency-based power management strategy. The proposed method is designed to achieve the load leveling/peak shaving advantage by the frequency-based charging/discharging intervention of the DC hybrid powered system.

As a result of the simulation, it is verified that the load frequency-based power management is able to provide effective load distribution scheme in terms of charging/discharging control of hybrid power systems, and it can protect the diesel-generator system from the sudden load variation which leads to tears & wears in mechanical system as well as poor quality of power in electrical system.

In terms of energy management of hybrid sources, the result of SoC represents that the energy state of SC/Battery is depending on the load variation tendency which is hard to estimate in the real world. Therefore, in practical application, it is necessary to study full-scale simulation which is combined of power management optimization in terms of fuel efficiency as well as the optimal capacity sizing of hybrid powers based on detail ship specifications and required missions.

References

[1] M. K. Zadeh, B. Zahedi, M. Molinas, and L. E. Norum, "Centralized stabilizer for marine dc microgrid," in *IECON 2013-39th Annual Conference of the IEEE Industrial Electronics Society*. IEEE, 2013, pp. 3359–3363.

[2] E. Skjong, T. A. Johansen, M. Molinas, and A. J. Sørensen, "Approaches to economic energy management in diesel–electric marine vessels," *IEEE Transactions on Transportation Electrification*, vol. 3, no. 1, pp. 22–35, 2017.

[3] O. Mo and G. Guidi, "Design of minimum fuel consumption energy management strategy for hybrid marine vessels with multiple diesel engine generators and energy storage," in *2018 IEEE Transportation Electrification Conference and Expo (ITEC)*. IEEE, 2018, pp. 537–544.

[4] J. F. Hansen, A. K. Ådnanes, and T. I. Fossen, "Mathematical modelling of diesel-electric propulsion systems for marine vessels," *Mathematical and Computer Modelling of Dynamical Systems*, vol. 7, no. 3, pp. 323–355, 2001.

[5] P. Dandeno, P. Kundur, S. Umans, I. Kamwa, H. Karmaker, S. Salon, M. Shah, and A. El-Serafi, "Ieee guide for synchronous generator modeling practices and applications in power system stability analyses," *IEEE Std. 1110–2002*, pp. 1–72, 2003.

[6] *Guide for Direct Current (DC) Power Distribution Systems for Marine and Offshore Applications*, ABS, Houston, TX, USA, 2018.

[7] K. Satpathi, V. M. Balijepalli, and A. Ukil, "Modeling and real-time scheduling of dc platform supply vessel for fuel efficient operation," *IEEE Transactions on Transportation Electrification*, vol. 3, no. 3, pp. 762–778, 2017.

[8] H. R. Karshenas, H. Daneshpajooh, A. Safaee, P. Jain, and A. Bakhshai, "Bidirectional dc-dc converters for energy storage systems," *Energy Storage in the Emerging Era of Smart Grids*, vol. 18, 2011.

[9] *Effects of AC Ripple Current on VRLA Battery Life*, Emerson Network Power, Columbus, OH, USA, 2015.

[10] K.-H. Chao, C. Tseng, H. Huang, and G. Liu, "Design and implementation of a bidirectional dc-dc converter for stand-alone photovoltaic systems," *energy*, vol. 4, p. 8, 2013.

[11] N. Omar, M. A. Monem, Y. Firouz, J. Salminen, J. Smekens, O. Hegazy, H. Gaulous, G. Mulder, P. Van den Bossche, T. Coosemans *et al.*, "Lithium iron phosphate based battery–assessment of the aging parameters and development of cycle life model," *Applied Energy*, vol. 113, pp. 1575–1585, 2014.

[12] D. Radan, "Integrated control of marine electrical power systems," Ph.D. dissertation, NTNU, Trondheim, Norway, 2008.

[13] J. J. May and H. Foss, "Power management system for the "deepwater horizon" a dynamically positioned all weather semisubmersible," in *Dynamic Positioning Conference, Marine Technology Society*, 2000.

[14] Q. Shafiee, T. Dragicevic, J. C. Vasquez, and J. M. Guerrero, "Modeling, stability analysis and active stabilization of multiple dc-microgrid clusters," in *2014 IEEE International Energy Conference (ENERGYCON)*. IEEE, 2014, pp. 1284–1290.

[15] M. Dewadasa, A. Ghosh, and G. Ledwich, "Dynamic response of distributed generators in a hybrid microgrid," in *2011 IEEE Power and Energy Society General Meeting*. IEEE, 2011, pp. 1–8.

[16] T. L. Vandoorn, B. Meersman, L. Degroote, B. Renders, and L. Vandevelde, "A control strategy for islanded microgrids with dc-link voltage control," *IEEE Transactions on Power Delivery*, vol. 26, no. 2, pp. 703–713, 2011.

[17] O. L. Osen, "Optimizing electric energy production on-board offshore vessels: Vessel power consumption profile and production strategies using genetic algorithms," in *OCEANS 2016-Shanghai*. IEEE, 2016, pp. 1–10.