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Published in:

Proceedings - 2019 IEEE 28th International Symposium on Industrial Electronics, ISIE 2019

DOI (link to publication from Publisher):

[10.1109/ISIE.2019.8781182](https://doi.org/10.1109/ISIE.2019.8781182)

Publication date:

2019

Document Version

Accepted author manuscript, peer reviewed version

[Link to publication from Aalborg University](#)

Citation for published version (APA):

Mutarraf, M. U., Terriche, Y., Niazi, K. A. K., Su, C-L., Vasquez, J. C., & Guerrero, J. M. (2019). Battery Energy Storage Systems for Mitigating Fluctuations Caused by Pulse Loads and Propulsion Motors in Shipboard Microgrids. In *Proceedings - 2019 IEEE 28th International Symposium on Industrial Electronics, ISIE 2019* (pp. 1047-1052). [8781182] IEEE Press. Industrial Electronics (ISIE), IEEE International Symposium on <https://doi.org/10.1109/ISIE.2019.8781182>

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Battery Energy Storage Systems for Mitigating Fluctuations Caused by Pulse Loads and Propulsion Motors in Shipboard Microgrids

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Abstract—In present times, the concerns over severe environmental pollution, fluctuations, and fossil-fuel consumption caused by immensely dynamic loads (pulsed loads) have captured attention in shipboard microgrids. In order to make such power system stable and reliable, presently, more generators are kept online that operate much below their efficient point. Therefore, in order to boost the fuel efficiency of shipboard microgrids, the minimum generator operation with N-1 safety can be considered as a possible solution, which is a trade off between reliability and fuel economy. For that, one of the efficient solution is to interface an energy storage system (ESS) by removing the backup generator or removing one of generator and operate rest of the generators close to their efficient point. Energy storage devices that have been frequently in use in different applications consist of batteries, flywheel, ultra-capacitor, and fuel cell. Lithium-ion among the different type of batteries is one of the most used battery in fully electric zero-emission commercial ferries that sails on shorter routes. This paper therefore presents Lithium-ion based Battery Energy Storage System (BESS) as a feasible solution to the prior mentioned concerns. At first, in order to cater with the fluctuation caused by the propulsion motor with the varying sea conditions, BESS is interfaced without the use of buck-boost converter in parallel with the DC-link capacitor. Secondly, the same BESS is interfaced with the point of common coupling (PCC) in order to cater with pulsed loads. The proposed methodology is simulated and verified using MATLAB/SIMULINK software environment.

Index Terms—battery energy storage system (BESS), shipboard microgrids, reliability, propulsion motor, fuel economy, pulse loads

I. INTRODUCTION

The shipboard microgrids can be considered as an islanded microgrid in offshore scenarios and when marine vessel is at shore and is connected to a nearby grid, it behaves as a grid-connected microgrid whose characteristics resemble to a terrestrial microgrid. The dynamic loads such as radar,

propulsion motors, electromagnetic gums, etc., in shipboard microgrids make it different from terrestrial microgrids. Moreover, the increase in electricity demand, fossil fuels, and emissions make such microgrids challenging and complex. Electrification in military and commercial ships is trending in recent times such that to improve efficiency and minimize the emissions produced by shipboard microgrids [1]. In 2012, the International marine organization (IMO) stated that NO_x and SO_x emissions for entire global shipping is about 13% and 15% respectively [2]. On the other hand, the CO_2 emissions for the shipping are found to be 2.2% of the entire global CO_2 emissions. Further, IMO forecasted that CO_2 emissions by 2020 could raise in between 50 to 250%.

The first diesel-electric based vessel *River tanker vandal* was developed in 1903. The modern electric propulsion for marine vessel came into existence when Queen Elizabeth II transformed from a steamship engine to a diesel-electric based integrated propulsion system. This transition from steam engines to diesel engines from the last century made it possible to minimize internal space dedicated for engines. Further, it helped to improve the reliability and efficiency as compared to steam based power generation. In the end of the 20th century, the advancement in power electronics helped to install electric propulsion drives that changes the design of entire ships. It helped to improve fuel efficiency, reliability, and reduction in space and thus resulted into All electric ships (AESs). This concept illustrates that electric power is generated from a power generation and feed through IPS to all the shipboard loads such as service loads, propulsion, radar, etc. The overall efficiency of the shipboard power system is improved that varies from 91.3% in case of induction motor and 92.3% for synchronous motor as depicted in Fig. 1.

In past, environmental concerns and the cost of energy

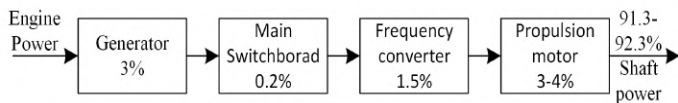


Fig. 1: Efficiency of a diesel-electric propulsion.

were not so important as they are of now in shipboard microgrids [3]. But in present times, the severe regulations imposed by IMO has compelled the marine industry to reduce the emissions and improve the fuel efficiency. Several solutions have been proposed, for instance: using alternative fuels, hybrid propulsion, and exhaust gases after treatment are among the most frequent applied methods such that to achieve the regulations imposed by IMO. However, these solutions are not found to be that beneficial for reducing the greenhouse emissions (SO_x , NO_x , CO_2 , etc.). Therefore, there is an increased demand to integrate zero-emission power sources such as energy storage systems (ESS) that should be explored for the shipboard microgrids. The evolution of shipboard power system is depicted in Fig. 2. In present, for the commercial ferries with shorter routes battery energy storage system (BESS) has already been adopted in the world with zero-emissions such as Ampere Ferry but in case of commercial vessels that sails for longer routes utilizing BESS as a sole power generation source is not possible. Thus, in such marine vessels ESS can be helpful in peak shaving, load levelling, power smoothing, Un-interruptible power supply (UPS), and black start applications. In this paper, BESS is interfaced in parallel with the dc-link capacitor in order to mitigate the power system fluctuations caused by variation in the sea conditions. Further, BESS is interfaced with the point of common coupling (PCC) in order to minimize the fluctuations caused by the pulsed loads within permissible limit.

The detailed modeling of diesel engine, active front end converter, lithium-ion battery, and pulsed load is illustrated in Section II. Section III describes the proposed methodology to cater with the fluctuations caused by the propulsion motors with the variation in the sea condition and pulsed loads. The proposed approach is verified in SIMULINK and the results are presented in Section IV.

II. POWER GENERATION SOURCES

A. Diesel engine governor

The diesel generator model comprises of three main parts: excitation system, diesel engine governor, and synchronous machine as depicted in Fig. 3. The power generation system needs some mechanism to control the voltage and/or current that is produced by the machine. By controlling the field current, output of the generator can be controlled. There are various excitation systems that generally include some mechanism for sensing and controlling the output voltage of a generator. The excitation system model generally provides the field voltage E_{fd} for a synchronous machine model and is

used to provide an initial magnetic field in order to start the synchronous machine.

Electric governors are used instead of mechanical governors due to unavoidable errors such as large inherent droop. In electronic governors as shown in Fig. 4, all blocks are electrical excluding actuator block due to which higher accuracy can be accomplished and a droop of around 0.5% as compared to 4% in case of mechanical governors. It is widely used in shore installations as well as in other platforms. The governor uses a feedback system in order to maintain and regulate the speed such that to maintain electrical frequency by setting the reference speed ω_f . The diesel engine governor Simulink model with a PI controller is shown in Fig. 5. The PI controller and actuator blocks are modelled in simulink by transfer functions with PI parameters K_i , K_p and time constants τ_1 , τ_2 , τ_3 , and τ_4 .

B. Battery Energy Storage Systems (BESS) electrical model

The battery models are mainly categorized as electrical circuit models and electrochemical models whereas rest of the models are derived from these basic ones such as dynamic battery model, which is derived from a simplified combination of electrical and electrochemical model. On the other hand, some researchers classified it into two other types, i.e., mathematical and analytical model [4]. The former one is simplified electrochemical based model such as Shepherd's equation whereas the later one is based on empirical data, for instance, Peukert's equation that include integrating current in order to improve battery model [5]. The reason of using electrical model in this paper is because of its accuracy that lies in between electrochemical and mathematical models with an error of 1–5% [6].

The equivalent circuit model of a battery comprises of three main electrical components, i.e., voltage sources, capacitors and resistors. These models are categorized as Rint model, Thevenin model (1st order), and double polarization model (2nd order) as shown in Fig. 6. Thevenin model or 1st order model uses an ohmic resistance and a RC parallel network in order to predict the response of a battery to a transient load event. It is considered as a good compromise between accuracy and complexity. The lithium-ion electrical based model utilized in this paper is shown in Fig. 7 in which ideal voltage source V_{oc} represents an open circuit voltage of a battery, R_{ct} is the polarization resistance due to concentration gradients, C_{ct} shunt capacitance, τ is the polarization time constant, V_{batt} is the terminal voltage, N_s and N_p are the number of cells in series and parallel circuit respectively.

$$V_{batt} = V_{oc} * N_s - \frac{N_s}{N_p} * I_{batt} * Z \quad (1)$$

where,

$$Z = R_{\Omega} + \frac{R_{ct}}{1 + \tau * s} \quad (2)$$

$$\tau = C_{ct} * R_{ct} \quad (3)$$

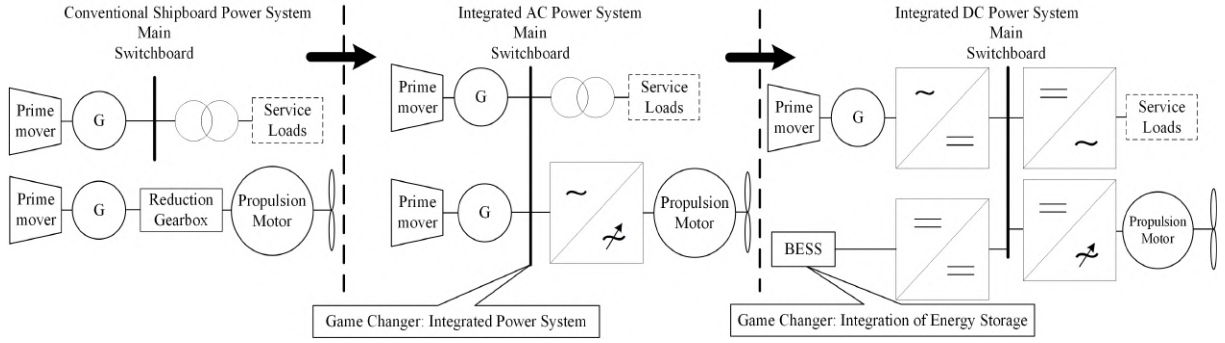


Fig. 2: Evolution of shipboard power system [3].

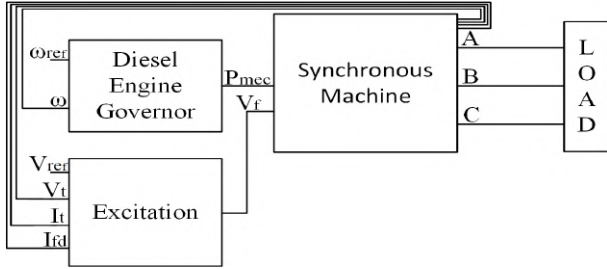


Fig. 3: Overview of a diesel-generator unit.

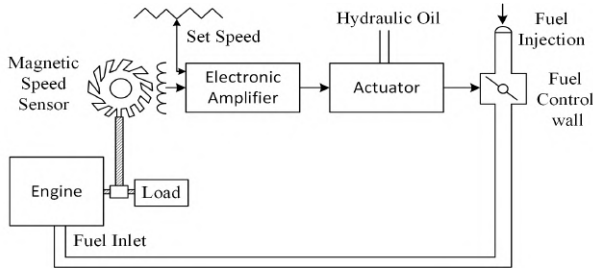


Fig. 4: Essential elements of diesel engine governor.

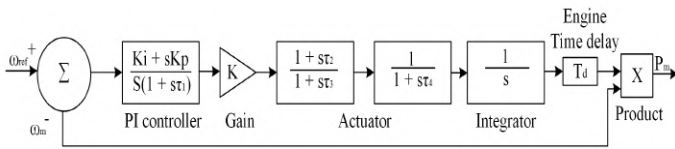


Fig. 5: Diesel engine governor simulink model.

C. Active front end converter and Inverter model

A variable frequency drive (VDF) delivers power from a source to the utility (motor in our case) in three steps, i.e., a rectifier (converts AC to DC), a DC link capacitor (smooths and store power), and an inverter (DC back to AC with variable frequency via pulse width modulation (PWM)). A rectifier is usually a six pulse type as it comprises of six diodes, though they are cost effective but they produces harmonics into the power system, which result into losses and additional heat. One solution might be to utilize multiple rectifiers based approach typically 12-pulse, 18-pulse, and 24-pulse in order

to reduce harmonics but it leads to an increase in cost due to an increase in number of diodes. The other solution might be to introduce passive filters, which adds low impedance in the system to absorb the harmonic frequencies. The disadvantages of this approach are: they utilize large amount of space and utilizes more energy than any other alternatives. An active front end (AFE) is an effective approach that not only minimizes the harmonics but also the cost. In this approach, instead of using diodes for AC-DC conversion, insulated gate bipolar resistors (IGBTs) are used, as these devices are controlled electronically that's why it's called "active" front end converter. The total harmonics distortion (THD) is reduced to 3%, which in conventional diode rectifiers is 25–30% [7]. The analytical based on controlled rectifier is depicted in Fig. 8, the current in the DC based can be expressed "(4)", where I_{s_a} , I_{s_b} , and I_{s_c} are the input currents, I_{inv} is the input current to the inverter, and the voltage at dc link capacitor can be calculated by the expression "(5)".

$$I_{rec} = S_a * I_{s_a} + S_b * I_{s_b} + S_c * I_{s_c} \quad (4)$$

$$C * \frac{d}{dt}(V_{dc}) = I_{rec} - I_{inv} \quad (5)$$

The analytical model of an inverter is expressed in "(6)" where V_{DC} represents the dc link voltage, and p_1 , p_2 , and p_3 are the PWM pulses signals applied to the inverter.

$$\begin{aligned} V_{s_a} &= 2 * \frac{p_1 - p_2 - p_3}{3} * V_{dc} \\ V_{s_b} &= 2 * \frac{p_2 - p_1 - p_3}{3} * V_{dc} \\ V_{s_c} &= 2 * \frac{p_3 - p_1 - p_2}{3} * V_{dc} \end{aligned} \quad (6)$$

D. Pulsed Load

The pulsed load such as electromagnetic guns, radars, and high-energy lasers can be modeled as a parallel combination of two resistances, i.e., R_1 & R_2 , where $R_2 \gg R_1$. An ideal switch is interfaced in order to choose between two resistances and is depicted in Fig. 9. The pulsed load on time is considered for two seconds in this research. As, R_2 offers a very high resistance, so load is considered as an open circuit, on the other hand, R_1 is a very small resistance, therefore the load can be

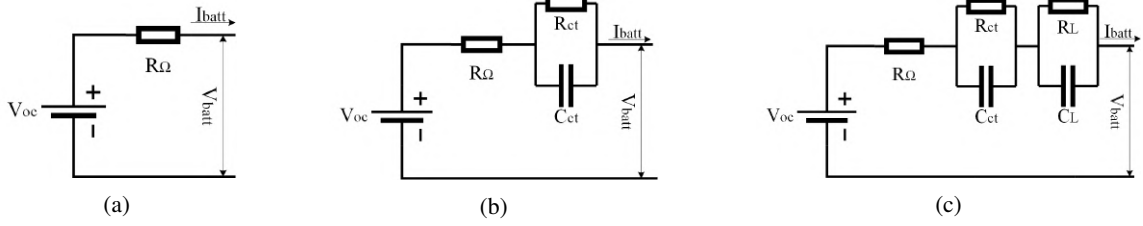


Fig. 6: Electrical circuit models (a) Rint model, (b) Thevenin model, and (c) Double polarization model.

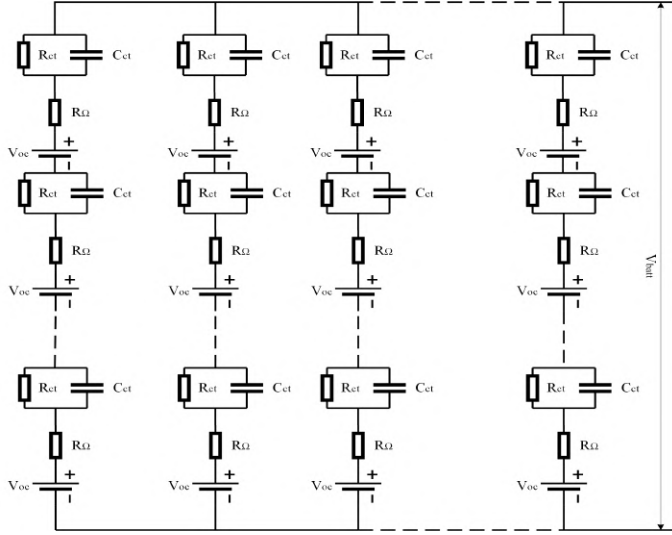


Fig. 7: Lithium-ion battery electrical model.

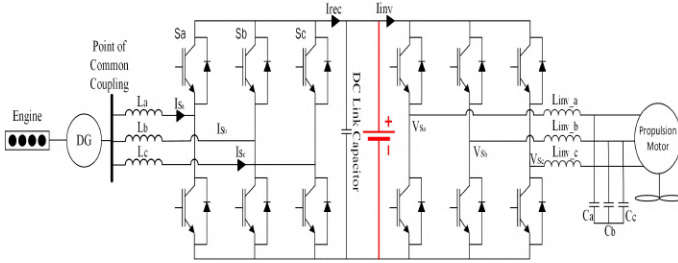


Fig. 8: A VFD based configuration for propulsion motor.

considered as a short circuit to shipboard power system such that it draws large amount of power for short duration of time. BESS is integrated with the PCC to mitigate the fluctuations produced by the pulsed load.

III. PROPOSED METHODOLOGY

The reason of utilizing BESS over other energy storage devices is the high energy density of batteries particularly Lithium ion. It can be inferred from the Table I that ultra-capacitors and flywheels offer high power density, hence they can be utilized only in those applications where delivering high power is required within short period of time. Among three propulsion systems, i.e., diesel-mechanical propulsion, electric propulsion, and battery propulsion, the overall efficiency of

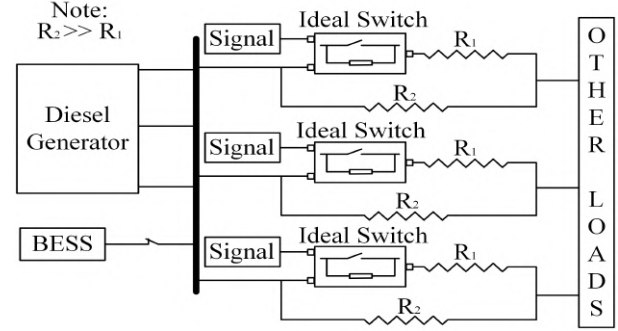


Fig. 9: Pulsed load model.

battery propulsion is better as compared to others as depicted in Fig. 9 [8] but using BESS as a sole generation source for ferries that sail on longer routes is not currently possible. BESS can be applied in several configurations in shipboard microgrids such as interfacing it at PCC, in parallel with the dc-link by using buck-boost converter etc. These configurations have been widely adopted in various applications. In this paper; BESS is interfaced directly in parallel with the dc-link capacitor without buck-boost and with the PCC in order to minimize the cost, reliability, and efficiency. As in marine vessels, majority of the power is consumed by the propulsion load, which is typically more than 70% and fluctuations in propulsion motor's power requirement can lead to a blackout. Further, Active Front End (AFE) converter is utilized in order to minimize the Total Harmonic Distortion (THD). The AFE converter is pledged for the power flowing between the diesel generator and the dc-link whereas the inverter is responsible for the power flowing between the propulsion motor and the dc-link. Therefore, any fluctuations that are caused by the change in the weather and sea conditions flow through the BESS.

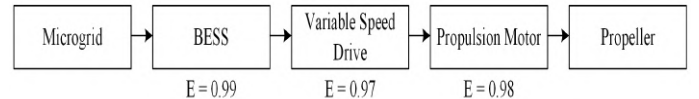


Fig. 10: BESS based propulsion.

IV. SIMULATION RESULTS

The power quality in shipboard microgrids is currently of main importance. The ship's crew go through various power

TABLE I: Technical features of ESS [9].

System	Power Density (kW/kg)	Energy Density (kWh/kg)	\$/kW	Efficiency (%)	Life Time (years)	Response Time
Li-ion	150–315	75–200	1200–4000	90–97	5–100	ms–s
Flywheel	400–1500	10–30	250–350	90–95	15–20	ms–s
Ultra-capacitor	100,000+	20+	100–300	85–98	4–12	ms

quality issues such as blackouts, voltage dips, fluctuations in frequency and voltage, flicker, and harmonics. Therefore, integrating AFE instead of six pulse diodes and BESS in parallel with the dc-link to minimize the distortions and fluctuations that are caused due to sudden changes in the sea conditions, which usually effect the power requirements. In order to verify the proposed approach, at 2.5 seconds, a heavy load is added that leads to sudden change in inverter output voltage, dc-link voltage, voltage at PCC and frequency as depicted in Fig. 11, Fig. 13, Fig. 15, and Fig. 17. At 2.8 seconds, BESS is interfaced in parallel to the dc-link and it can be clearly seen in Fig. 12, Fig. 14, Fig. 16, and Fig. 18 that fluctuations are minimized within the standard limits. Further, Fig. 19 illustrates the current drawn from battery and in Fig. 20 pulsed load is added at 2.8s and due to the fluctuations BESS is brought online to cater with it.

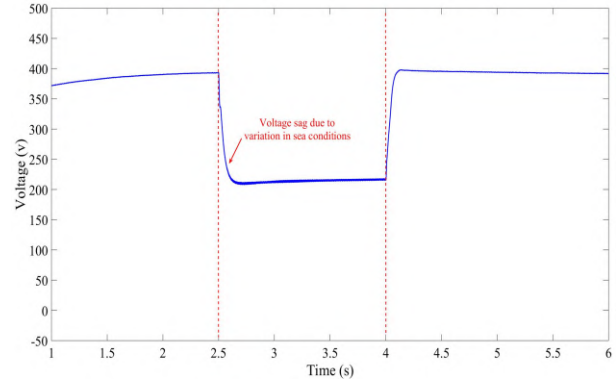


Fig. 13: DC-Link voltage without BESS.

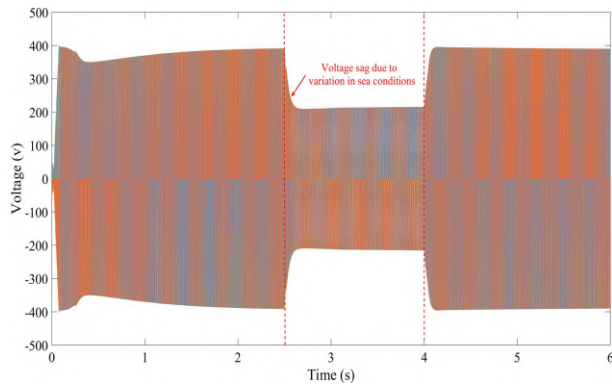


Fig. 11: Inverter output voltage without BESS.

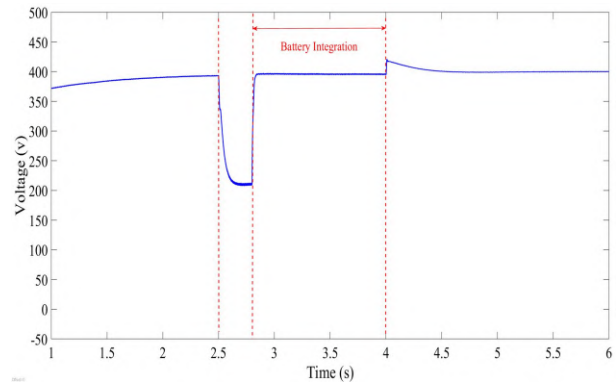


Fig. 14: DC-Link voltage with BESS.

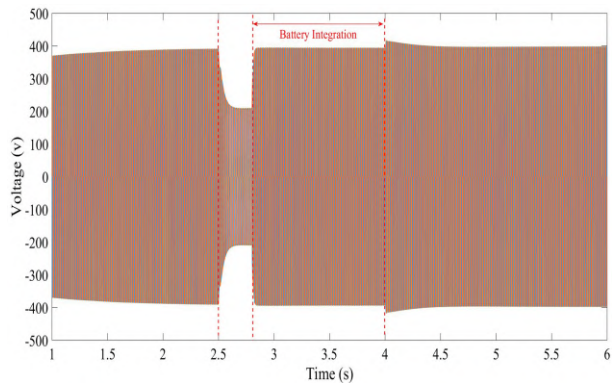


Fig. 12: Inverter output voltage with BESS.

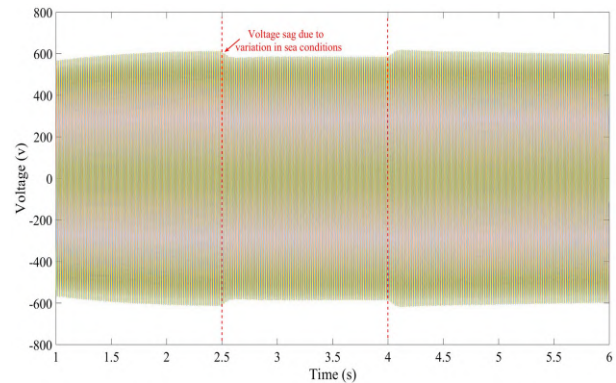


Fig. 15: Impact of variation in sea condition on voltage at point of common coupling without integration of battery.

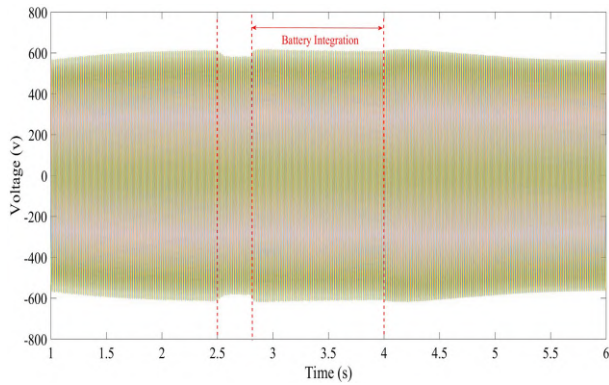


Fig. 16: Impact of variation in sea condition on voltage at point of common coupling with integration of battery.

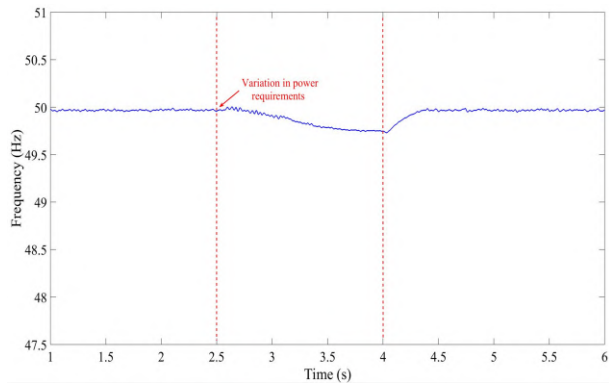


Fig. 17: Frequency in case of variations without BESS.

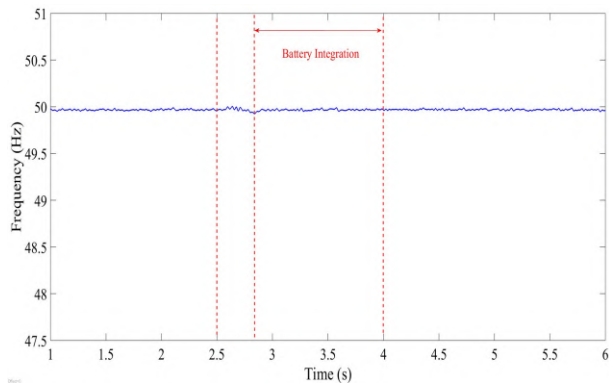


Fig. 18: Frequency in case of variations with BESS.

V. CONCLUSION

This paper presents a novel approach for ferries that sail for longer routes. In this approach, firstly BESS is integrated directly without using buck-boost converter in parallel with the dc-link capacitor in order to mitigate the fluctuations caused by the changes in the sea conditions. Further, AFE converter is used in order to minimize the THD. As in these marine vessels, it is found that propulsion motor consumes more than 70 % of the overall load and any fluctuation in the power requirement of the propulsion motor has huge impact on the

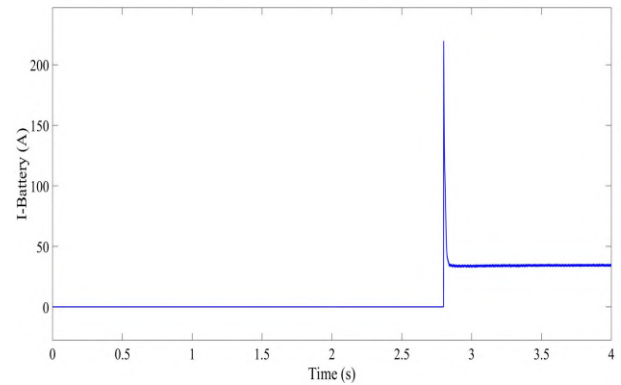


Fig. 19: Battery current with and without BESS.

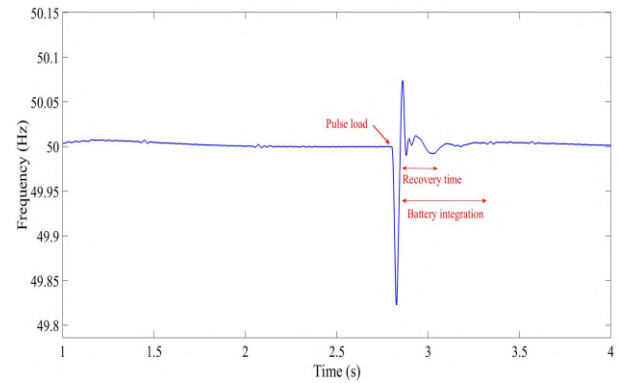


Fig. 20: Impact of pulsed load on the frequency at PCC.

shipboard microgrid. Secondly, BESS is interfaced with the PCC in order to cater with the fluctuation caused by the pulsed loads. The simulation results shows that by integrating BESS the fluctuations can be easily be minimized without bringing backup generator online.

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