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Energy Management System with Temperature Rise Prevention on Hybrid Ships

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***Abstract*—**Marine shipping has now become one of the major worldwide contributors to pollution and greenhouse gas emissions. Hybrid ships technology based on multiple energy sources has taken a great scope of research to get rid of ship emissions and cut down fuel expenses. Insufficiency between power generated and the demand load to withstand the transient behavior on ships during severe climate conditions will lead to a blackout. Thus, an efficient energy management system (EMS) is a mandatory scope for achieving higher system efficiency while enhancing the lifetime of the onboard storage systems is another salient EMS scope. Considering energy storage system conditions, both the battery state of charge (SOC) and temperature represent important parameters to prevent any malfunction of the storage system that eventually degrades the whole system. In this paper, a two battery packs ratio fuzzy logic control model is proposed. The overall aim is to control the charging/discharging current while including both the battery SOCS and temperature in the energy management system. The full designs of the proposed controllers are described and simulated using MATLAB. The results prove the successfulness of the proposed controller in stabilizing the system voltage during both loading and unloading while keeping the energy storage system in a healthy condition.

***Keywords*—**Energy storage system, fuzzy logic control, hybrid ships, thermal runaway, energy management system.

I. INTRODUCTION

THE fast growth of electric and hybrid propulsion systems introduces new developments in energy storage systems (ESS). There are different ESS sources with different characteristics and different operating conditions such as charging and discharging time, operating temperature and response time. A lot of research work has been provided in recent years, especially in the last decade, to improve ESS capacity. Storage capabilities have been improved by using two or more ESS technologies. A Hybrid Energy Storage System (HESS) is an important solution for mitigating transients in shipboard power systems in an effective and efficient manner. In some applications, like offshore vessels in a dynamic positioning (DP) operation, faults can lead to the blackout [1]. Thus, HESS on shipboard power systems is used as a power generation source for load levelling, peak shaving, and for reducing voltage and frequency deviations, which consequently may contribute in enhancing the power quality of the electrical power system [2]. The power management system (PMS) scope is to provide a sufficient power for essential operations, and to preserve loads in case of insufficient generator capacity. Energy management system contributes in automatic functions such as stop running generators, or to disconnect generator breakers effectively. Considerations are to be given to techniques such as power limiting of heavy consumers, shedding of non-essential loads and thrust reduction to maintain the availability of power. Furthermore, different conditions of storage systems must be controlled since the increase in temperature beyond the allowable limit leads to hazardous consequences. Therefore, a battery management system (BMS), as included in an energy management system, plays an importance role in the monitoring system. The relationship between battery operation and their degradation and service life is complex and not well known [3]. There is a lack of awareness about the best practices that influence service life and degradation as each type with different condition leads to different results. Battery degradation must be taken into consideration as batteries can contribute to over 25% of the product cost for electronics, over 35% in electric vehicles, and over 50% for power supplying application.

According to literature, the modes that lead to blackout on dynamic positioning vessels by using the protection of generator signals have been studied in [4]. Power management functionality on dynamically positioned vessels has been proposed in the same paper using thrust allocation method, where it is achieved by reducing frequency and load variations on the ship. However, this reduces the ship capability as well. The fuel consumption has been minimized via an optimization problem in [5]. Flywheel energy storage system technology has been used to build load dependent start tables, as the orders depending on only the starting of loads to prevent blackout. Also, fast load reduction techniques have also been addressed and a closed bus-tie connection to maximize flexibility of the grid to achieve maximum fuel saving has been connected. Phase locked loop (PLL) is used for the synchronization between the voltage inverter and the ship's electrical power grid in [1], as a solution to mitigate power quality problems and to get rid of the decreased power capability of the network, but without taking into consideration the high frequency power requests. An Energy management system with hybridization of energy source on ship has been studied in many researchers. A Proportional-Integral (PI) controller management strategy to generate power references for controlling the network depending on state of charge (SOC) has been addressed in [6]. This work concluded that it can prolong lifetime of HESS as the

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time constant of the low pass filter is variable with SOC. In [7], the results proved that the use of DC voltage can help in managing the loads with the generation effectively, and that it is more efficient than AC power, that is why energy storage system (ESS) is applied to make it a purely constant DC value. Fault protection, power sharing and many other considerations have been taken to prove that DC is better. They concluded that ESS increases generator efficiency and life time and decreases maintenance. It also discussed the benefits of a closed bus tie grid and how it can be controlled and its effect on shipboard micro grid [8]. A HESS has been used in order to get rid of drawbacks of the storage system that uses one type of energy. A review is conducted for the methods that control that kind of ESS depending on operation and types of ESS [9]. Passive control of energy storage systems has been used in [10], as the battery with ultra-capacitor is proposed to mitigate high energy weapons in propulsion ships. Also, it shows the benefits for reducing the number of running generator sets. Active control has been used in [6], energy management strategy based on SOC is proposed for HESS in electrical networks to decrease the DC bus voltage fluctuation using low pass filter.

As a solution to solve the charging and discharging stress problems, dual groups have been imposed in [11], where the secondary and primary dual packs were chosen with different ratings. It was concluded that the method has helped in reducing battery stresses and prolonging battery life time by using a PI controller. Three parallel energy sources are discussed in [12]. That paper showed the necessity to produce zero-emissions of carbon in a fully electric power cargo vessel. Energy storage system based on battery banks has been investigated starting from the design through to the expansion proposal if needed. Also described in this work is the design of PMS and BMS for a cargo vessel equipped with the three-energy source system. By using model-based predictive control, it was concluded that it could help in reducing the impact of carbon on the environment.

For extending the lifetime of a battery storage system, many experiments have been carried out to conclude the effect of different stress factors on battery degradation as in [13]. Temperature is the most critical factor that affects the storage system as concluded in [14], where thermal runaway can lead to failures in the storage system and can harm humans in the area resulting from the explosions and fire that may happen.

From the above literature search, it can be concluded that to date there is no study that includes the ESS temperature effect with energy management algorithms to reduce the grid power imbalance. This paper proposes an approach to monitor and control the temperature with shipboard grid loading and unloading. Specifically, a dual HESS topology and its associated power management strategy to mitigate the charge/discharge stress on a battery with respect to the energy storage system SOC and temperature is proposed. In this study, an approach to decrease the system imbalance by controlling the power absorbed/supplied by the storage system using different fuzzy logic controllers is investigated to check the feasibility of implementation on an actual shipboard grid. The study aims to increase the efficiency and support the designers in the modeling process before constructing the ships. This will consequently reduce the grid imbalance and will lead to a reduced grid management cost. This overall objective will be fulfilled through two-level EMS-FL controllers. The first controller detects the grid imbalance where a shipboard model will be designed to apply the controller. The second controller monitors and controls the temperature, current and SOC of the battery packs.

This paper is organized as follows. Following the introduction, the algorithms and controller description, energy management method and dual pack solution are presented in Section 2. Results and discussions are presented in Section 3. Finally, the conclusions are presented in Section 4.

II. PROPOSED MODEL DESCRIPTION

An energy management system must be capable of providing sufficient power for essential operations, and to prevent loads from starting in case of insufficient generator capacity. The basic way to accomplish this task is to control the converters which are subjected to a PMS. The energy management storage system (EMSS) is to be placed below the EMS system in the control hierarchy, since SOC and other battery parameters, such as temperature, SOC, and the current level, are necessary for the control. The consequences of battery faults can be eliminated by the EMSS and can be corrected by the EMS, as the former prevents the battery from operating outside its safe operational range. Generally, the constructed models that simulate the chemical reactions inside the lithium-ion cells are complex models and take a lot of time for detecting accurately the faults inside the cell. All of these faults can affect the battery temperature condition and degrade its lifetime. Any fault inside or outside the cell leads to thermal runaway that affects the storage system application and the users. Internal faults can be detected from the abnormal responses from the battery operation, which include significant voltage drop, increasing in self discharging rate, quick temperature rise, and increase in internal resistance [15]. In this study, a fuzzy logic-controlled system will be used to manage the operation of the overall energy system and energy storage system. This system will maintain the operation of the storage system within the allowable operating conditions to prevent any damage that might be caused by excessive temperature and will find a solution for supplying the loads in the case of energy storage system temperature rises as any fault inside or outside the battery leads to temperature rise.

A. Energy Management System on Hybrid Ships

The energy management strategy in energy ship technologies has become a popular research field and one of the promising development directions to the utilization of the energy resources and to reach the highest efficiency with increasing lifetime and decreasing maintenance cost. Among these technologies, fuzzy logic (FL) has been used in many different applications where outputs are produced from non-linear inputs [16]. The fuzzy logic system consists of fuzzification, inference process, and defuzzification. The fuzzification is converting input of the fuzzy logic controller into fuzzy-based data on the membership function. The inference process is to convert data on membership function and combine it with the fuzzy rules to get an output. In this control strategy, it consists of two FLCs; the first controller is for the energy management system (EMS-FLC), while the second one is for the energy management storage system (EMSS-FLC). The latter controller provides the total reference power for the battery and supercapacitor for charging or discharging. A low pass filter is then applied to separate the power reference into a low frequency component (battery power reference) and a high frequency component (supercapacitor power reference) as shown in Fig. 1. The battery power reference is passed through the second stage EMSS-FLC of through power sharing controllers that distribute the battery power reference into multiple batteries, based on the SOC and temperature. Fig. 1 represents the overall proposed control scheme which is explained as follows:

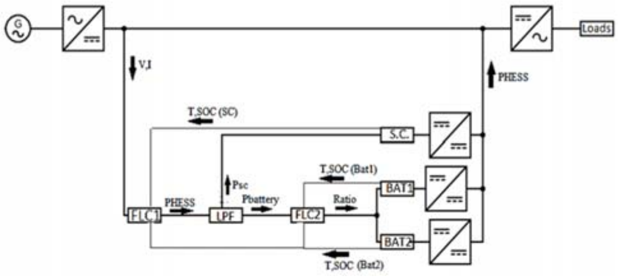


Fig. 1 Overall proposed control scheme

i. EMS-FLC (First Controller):

The inputs and outputs for this controller are shown in Fig. 2.

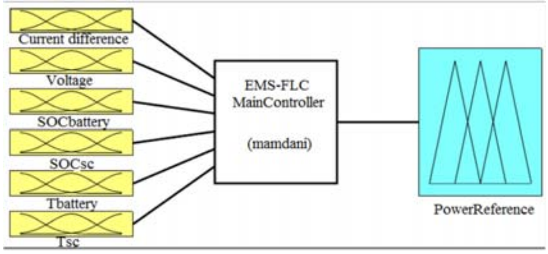
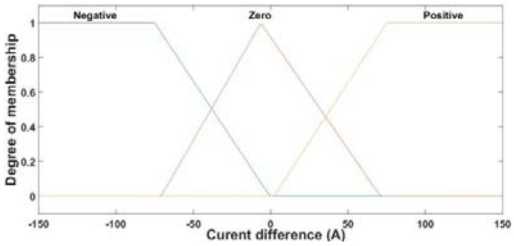
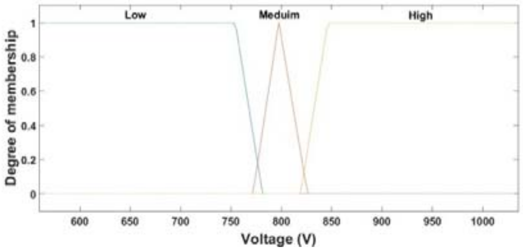


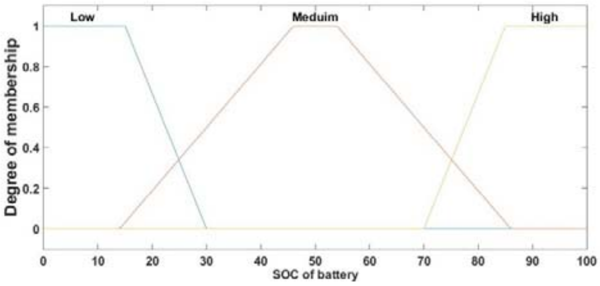
Fig. 2 The Detailed Proposed Fuzzy Logic Controller-1



(a)



(b)



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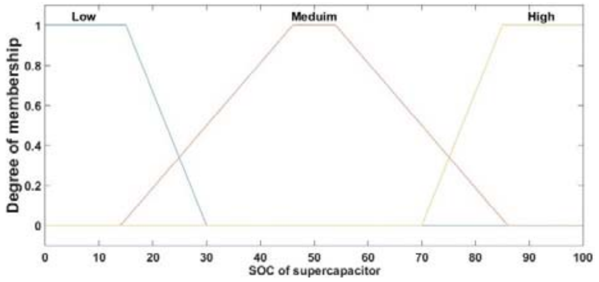
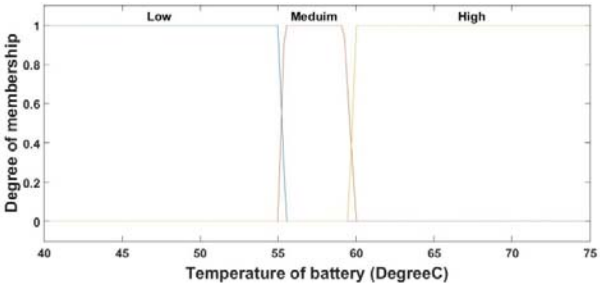
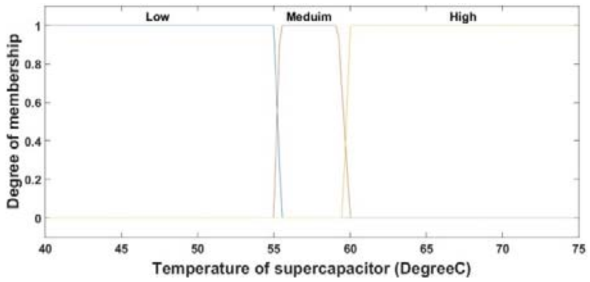


(d)



(e)



(f)

Fig. 3 Inputs Membership of the first fuzzy logic controller (EMS-FLC)

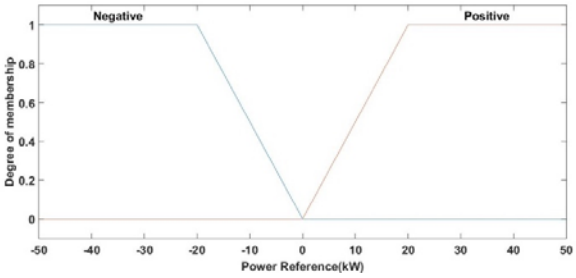


Fig. 4 Outputs Membership of first fuzzy logic controller (EMS-FLC)

The controller produces the total power reference to meet the demand power. The input variables are the current difference between the generated and the actual load demand. The membership functions of the DC bus voltage, the SOC of the battery and supercapacitor and temperature of battery and supercapacitor are shown in Figs. 3 and 4. Both the current difference and DC voltage determine the reference power and both SOC and temperature of the battery and supercapacitor are adjusting the reference power for the HESS, as the temperature protects the ESS from any excess C-rates that may lead to thermal runaway. The C-rate is a measure of the rate at which a battery is discharged relative to its maximum capacity. The current must be controlled reference to battery temperature, but SOC protects the ESS of over discharging/charging. Three membership functions (Negative, Zero and Positive) are chosen for the current difference as shown in Fig. 3 (a). The membership function limits are −150A (charging condition) as a Negative membership and 150A (discharging condition) as Positive membership function and both with trapezoidal shape. For the zero membership function (balancing condition between generation and loads), a triangular shape is drawn. For the DC voltage variable, three membership functions (Low, Good and High) are chosen as shown in Fig. 3 (b). It represents the under voltage (Low membership function with trapezoidal shape) and over voltage situation (High membership function with trapezoidal shape). For Good membership function, triangular shape is chosen and it represents nominal voltage condition. For the SOC input variable for battery and supercapacitor as shown in Figs. 3 (c) and (d), Low membership function means that an over discharging condition will occur, while Medium membership function is the safe operating region and High membership function means that an over charged condition will occur. For the temperature membership of battery and supercapacitor are shown in Figs. 3 (e) and (f), it has been chosen as a trapezoidal shape. Low, medium and high memberships represent the importance of controlling the storage system power; Low means that the importance to control supply power is low, medium means temperature starts in a critical stage and it has a medium importance to control the packs, while High means a forbiddance to supply power because it reached higher temperature level. For the output variable as shown in Fig. 4, power reference, Negative and Positive membership functions represent charging and discharging condition with trapezoidal shape, while Zero membership function with a triangular shape represents the balanced condition.

A set of 82 rules has been constructed. For example, if the voltage is low, the current difference is negative, the temperature of battery is high and the temperature of supercapacitor is high, then the power reference is zero. This means that the controller will provide no reference power for discharging although the voltage is low and the current is negative as the temperature of the battery and supercapacitor are high. It also shows that the controller saves the HESS from explosion. The reason of the temperature feedback from the two energy sources is to produce zero output signal in case of high temperature on both the energy storage systems at the same time. All other remaining rules can be seen from the surface plot shown in Fig. 5. This figure demonstrates the output signal of controller on the y-axis, while the x-axis includes two inputs; the current difference and the battery temperature. For instance, in case of low temperature (35^{o}C) the resulting power reference sign will be the same as the current difference sign. This means that if the system needs an excessive discharging power (positive sign) from the storage system the power reference will be positive and the magnitude value is a direct relation with grid power imbalance value, but at high temperatures with the same current difference value, the controller will produce zero reference output signal to save the storage system from any failure.

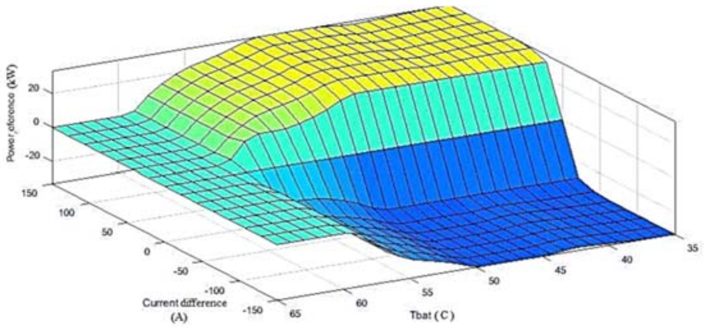


Fig. 5 Surface Plot of FLC 1

B. Temperature Rise and Its Effect on EMS and Ship Control Efficiency

The energy management system on hybrid ships must collect data from generation, ESS and loads. The HESS is hybrid ships must be controlled and monitored in order to achieve highest efficiency and increase the lifetime of HESS. Battery operating mode is determined based on its SOC; hence, the battery SOC must be taken into account in the power management algorithm. The battery system has three modes due to the bidirectional power flow, which are battery discharging mode, battery charging mode and battery standby mode (SOC out of limit). Temperature highly affects battery capacity, charge and discharge rate [17]. When the temperature continuously rises exceeding 80^{o}C, the battery experiences first stage of thermal runaway [18]. In this condition, the battery may cause fire, smoke, and even an explosion by the final stage [14].

During the charging and discharging, the internal chemical responses increase the temperature [19]. This added heat energy affects the battery life, reliability, and performance on higher temperature. The experiments proved that battery capacity increases with the rise of temperature, but the more the temperature exceeds the operating limit, an increase in the solution evaporation rate occurs [16]. Temperature can rise due to several reasons such as operationally and environmentally, and both must be considered in a management system algorithm.

C. Battery Pack Model Design

The MATLAB/Simulink based on an SSC_LITHIUM_2RL model has been adopted in this study. Fig. 6 shows the charging/discharging current applied on battery.The model is shown in Fig. 7 and it represents a lithium battery with temperature dependent where it implements the elements of an equivalent circuit model with two RC branches [8]. A battery pack can be modeled by connecting multiple copies of the battery cell block in series. For the proposed temperature dependent model, Fig. 8 shows the response of the temperature with regard to the applied current of Fig. 6. Four cells have been connected in series to simulate the thermal behavior of the cells together and with environment temperature by convection. The temperature of the lower cell is monitored and controlled with the proposed fuzzy logic controller (EMSS-FLC). By applying the current profile of Fig. 6, the effect of temperature rise has been studied before applying the proposed controller as shown in Fig. 8. Consequently, an extreme temperature has occurred reaching 90ºC on battery group that increases the probability of cell failure.

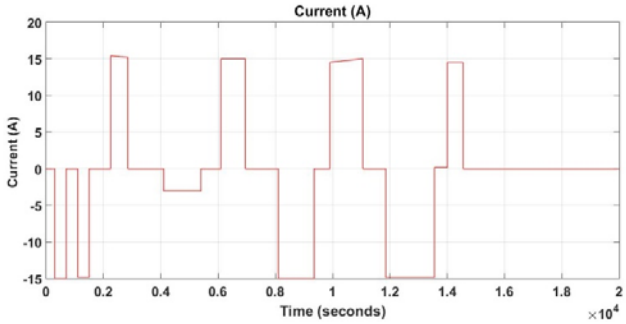


Fig. 6 Charging/Discharging current applied on battery

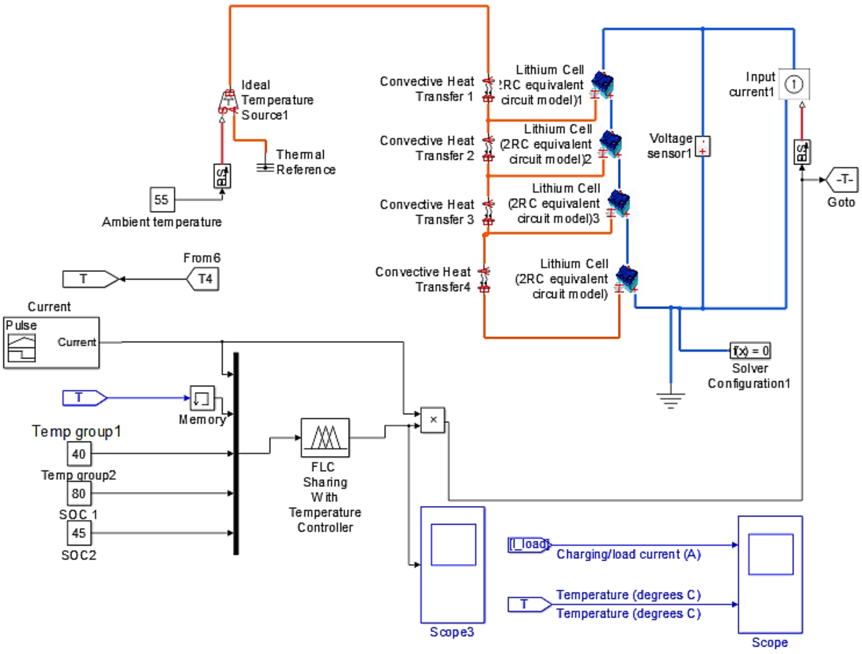


Fig. 7 Temperature dependent model

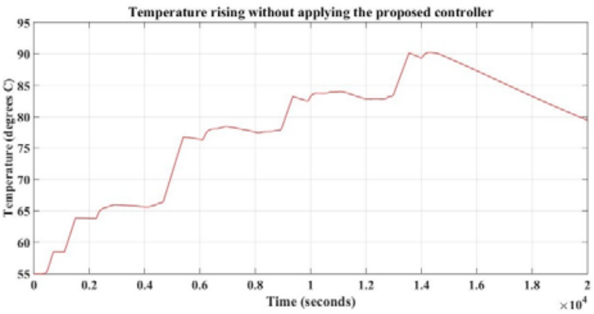


Fig. 8 Resulting temperature before applying the EMSS-FLC

D. Shipboard Model Design

The model is designed to study the controller with three main parameters; temperature, SOC, and current to investigate the effect of the proposed model. As mentioned in Table I, the shipboard consists of synchronous generator (60kVA), in series with two loads with ratings 30 kW and 60 kW. For testing the loading and unloading with HESS support, the generator rating is set to be lower than the summation of the two loads, so the effect of the added HESS with the proposed controller will be tested.

TABLE I
POWER SOURCES AND LOADS RATING

Equipment	Quantity	Power	Timing (sec)
DG	1	60 kVA	-
Load1	1	30 kW	From 0 to 1
Load2	1	60 kW	From 0.1 to 0.25
Battery	2	100 Ah	-
Supercapacitor	1	500 F	-

III. A SOLUTION FOR TEMPERATURE RISE USING DUAL PACKS

Dual pack can be used to reach the highest efficiency [11], as two packs are already used on the ship port side and star port side [2]. The shipboard is already divided into two or more sections in order to achieve the system redundancy. Closed bus-tie is already proposed and it proved that it can increase the grid efficiency and decrease operation cost [8]. Using dual pack is proposed in this work in order to mitigate the disadvantage of the ESS group when facing any malfunction especially under temperature rise and SOC over charging /discharging.

A. EMSS-FLC (Second Controller)

For power sharing between a two-pack controller: the proposed model coordinates between two packs in order to continue supplying power in any condition. This fuzzy logic controller is used when there are multiple batteries and supercapacitors. The aim of this control strategy is to allocate reference power among multiple energy storages based on the SOC of the batteries and supercapacitors and temperature. Using fuzzy logic controller, the system will automatically stop the operation of the battery at high temperatures, as well as, low SOC on discharging. This condition will continue until the temperature of the battery is normalized.

The fuzzy controller is shown in Fig. 9, while Fig. 10 (a) is showing the total power reference of the battery, the SOC of the battery groups are shown in Figs. 10 (b) and (c), and the temperature of the battery groups are shown in Figs. 10 (d) and (e). For the output is the sharing coefficient as shown in Fig. 11. The power sharing coefficient (sharing coff) which divides the total battery reference power (PBatref) into two power references (Pgroup1, Pgroup2) for the two battery groups is given in (1) and (2).

$$Pgroup1 = sharing\ coff * PBatref \qquad (1)$$

$$Pgroup2 = PBatref - Pgroup1 \qquad (2)$$

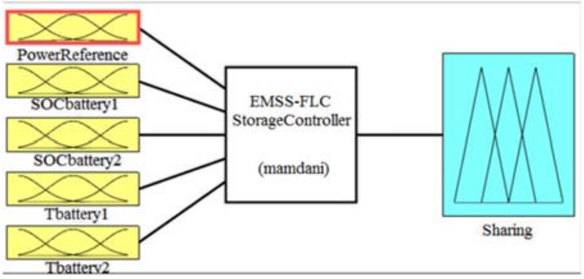


Fig. 9 Detailed Fuzzy Logic Controller2

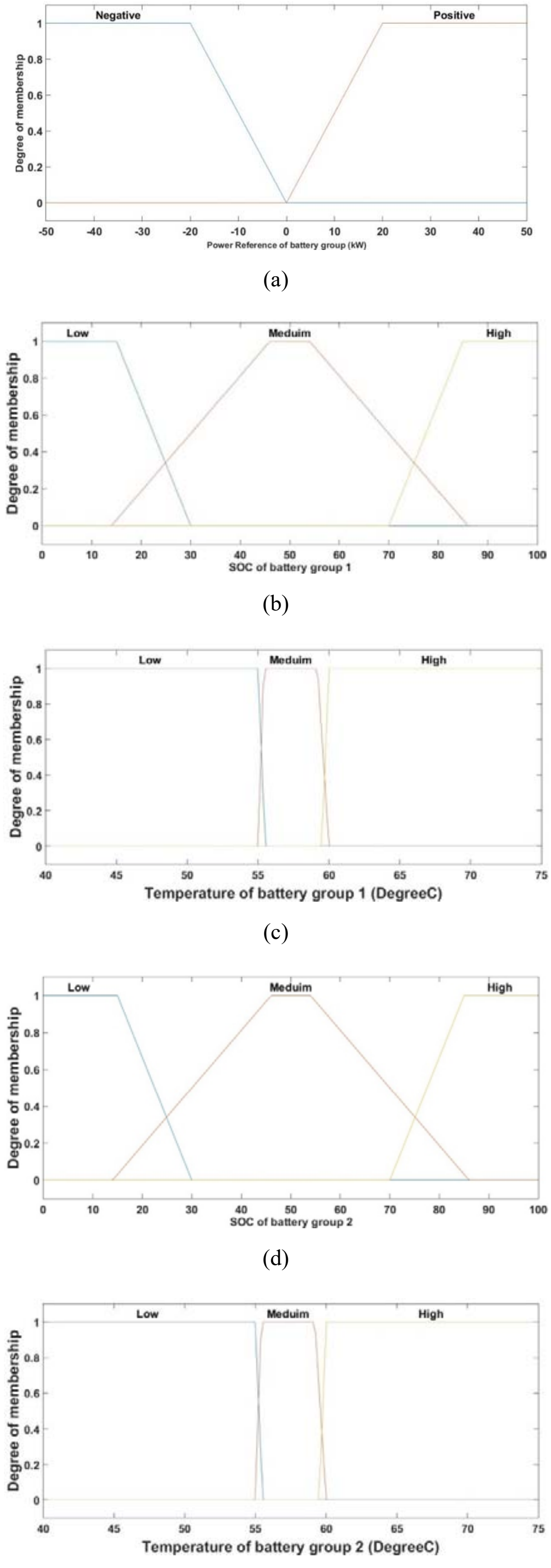


Fig. 10 Input Membership of the second fuzzy logic controller (EMSS-FLC)

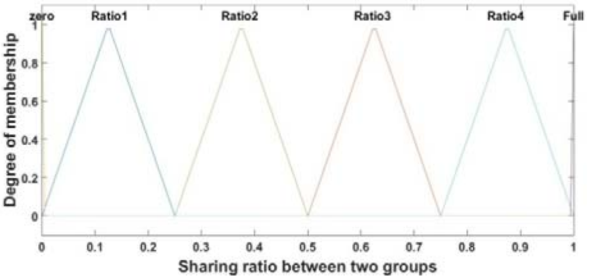
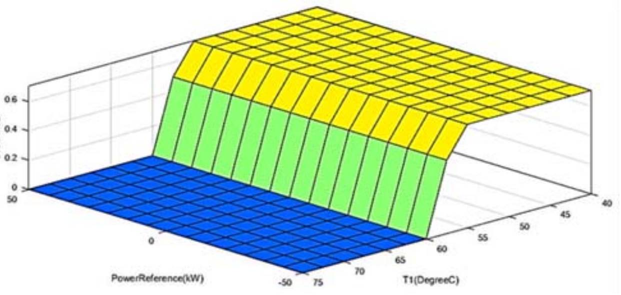


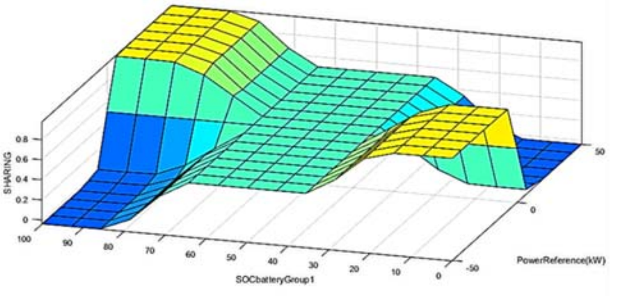
Fig. 11 Output Membership of the second fuzzy logic controller (EMSS-FLC)

The membership functions of the total battery reference power are listed as negative and positive trapezoidal shape. It means the negative and positive reference power for charging and discharging, respectively. The trapezoidal shape membership functions of the SOC of the batteries are listed as low, medium, high. For temperature membership, the triangular shape is chosen for low, medium and high for operating/ambient temperature. The triangular membership functions of the output variable, sharing ratio is chosen. They represent different power sharing ratios of the batteries at different conditions of SOC and temperature. The output consists of six memberships that make the output signal more specific and accurate regarding to input signals. The fuzzy first rule example is as follows: IF battery reference power is Negative and group 1 battery SOC is High and group 2 battery SOC is Low then the Sharing ratio will be 4. This means that the maximum discharging power of the battery will be supplied by the first battery (the higher sharing ratio) and the rest of the power will be supplied by another battery. But in case of high temperature of group 1 the ratio will differ as group 2 is healthier, zero power is the reference for the first and the other will take the full power reference of the batteries.

The membership functions surface plot of the output variable is shown in Fig. 12. There are 145 rules that have formatted a decreasing sharing ratio relation with the temperature rising as shown in Fig. 12 (a). While it is shown in Fig. 12 (b) that the sharing ratio has a direct relation with SOC; as SOC decreases the sharing ratio also decreases. The proposed constructed rules are resulting in the surface diagram shown in Fig. 12 (a), This figure shows that in the case of increasing temperature from 40ºC till reaching 60ºC in the storage system, the resulting sharing ratio (output) of the controller is decreasing until it reaches zero to prevent thermal runaway. For Figs. 12 (b) and (c), illustrate the demand power reference of the battery group (on x- axis), the positive sign means discharging and negative sign means charging, while the SOC of the battery group is on the y-axis and it starts from zero (empty battery) to one hundred (charged battery). For example, in case of medium SOC (50%) on battery group one and medium SOC (50%) on battery group two, this means that group one and group two must share equally the value of the total power reference; therefore, the sharing coefficient (on Z- axis) is 0.5, which means that, the power of group one when charging is equal to 0.5* total power reference and the power of group two when charging is equal to 0.5* total power reference. On other hand, in case of low SOC (25%) on group one and high SOC on group two (70%), this means that the sharing coefficient is increasing from 0.5 to 0.7, so that, the charging power of group one = 0.7* total power reference and charging power of group two = 0.3* total power reference.



(a)



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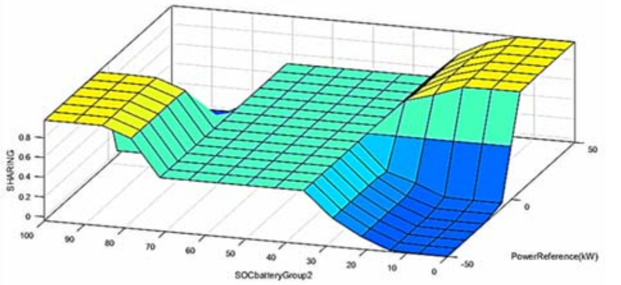
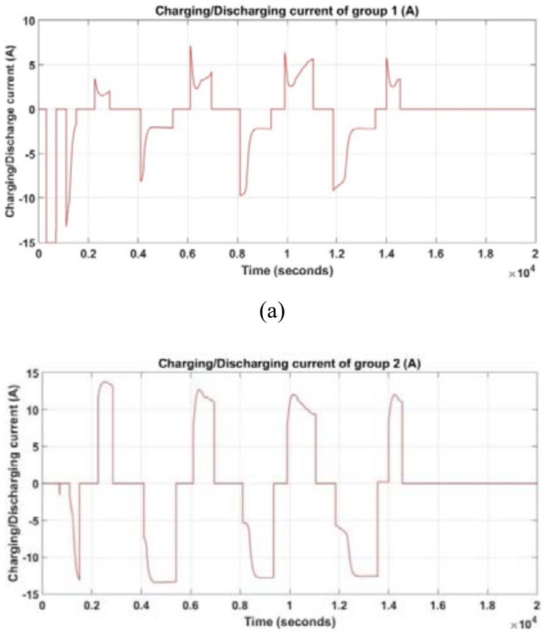


(c)

Fig. 12 Surface plot of FLC2

IV. RESULTS AND DISCUSSION

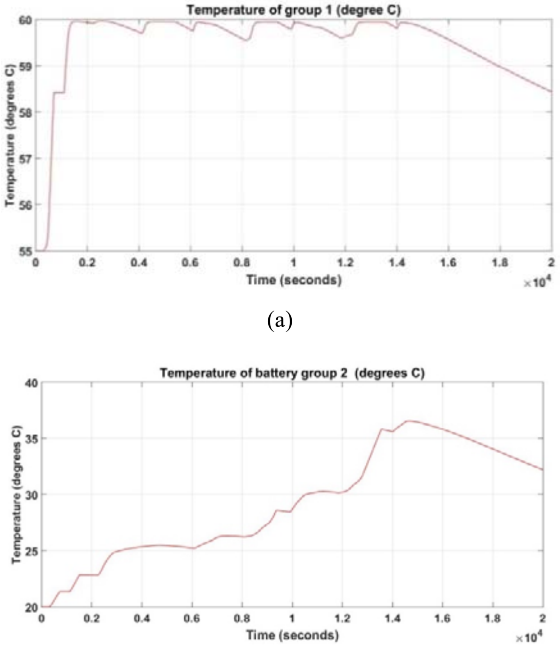
The results are discussed and shown in this section. Referring to section II C, it is simulated that the starting ambient temperature of group one is 55ºC which is defined as a medium membership in the proposed controller as shown in Fig. 7, while Fig. 13 is showing that the temperature has been stabilized after adding the proposed fuzzy logic controller (EMSS-FLC). Figs. 13 (a) and (b) are showing that the proposed model reproduced the current signal between the two groups as referred in equations (1) and (2), in order to save battery group one from any increase in its temperature. The mentioned proposed controller (EMSS-FLC) is resulting in a positive effect on the temperature of the two groups. As group one is facing high temperature values, it is kept at a temperature levels below 60ºC as shown in Fig. 14 (a). On the other hand, group two is beginning from a normal temperature condition (20 ºC), it is charging/discharging normally without its temperature rising above 40oC as shown in Fig. 14 (b).



(a)

(b)

Fig. 13 Current reshaping after applying the proposed model



(a)

(b)

Fig. 14 Temperature responses with proposed model

Referring to section II D, the shipboard model consists of two fuzzy logic controllers; the first controller (EMS-FLC) is to sense and to generate the reference power that mitigates the power imbalance, while the second fuzzy logic controller (EMSS-FLC) divides this reference power into two groups with regards to the battery SOC and battery temperature of each group. When the voltage drops because of the loading condition, the first fuzzy logic controller (EMS-FLC) senses this voltage drop and then the controller produces a total power reference to normalize the voltage level again. While the unloading condition at 0.25 sec, an overvoltage occurs that leads the controller to produce a total power reference to start charging the HESS. An illustration of the three waveforms that mitigate the grid power imbalance, which are; the total power reference of HESS as shown in Fig. 16 (a), power reference of supercapacitor as shown in Fig. 16 (b) and power reference of battery as shown in Fig. 16 (c). Comparing Figs. 15 and 17, Fig. 15 is showing the voltage drop because of the loading and unloading in the grid without using HESS, while in Fig. 17 is showing a stable DC voltage because of using HESS with the proposed controllers.

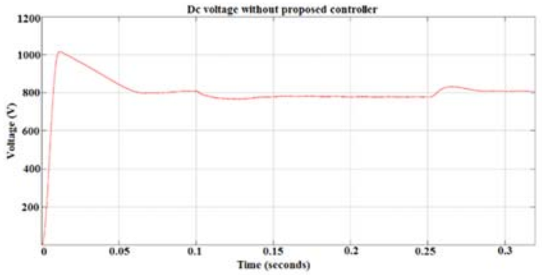
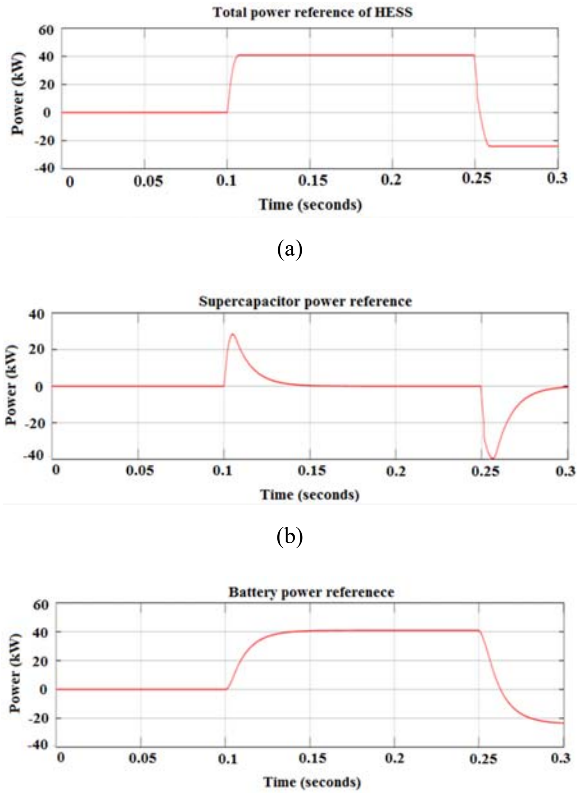


Fig. 15 DC voltages without using proposed algorithm



(a)

(b)

(c)

Fig. 16 Total power references of first controller with LPF

The SOC of group one has been simulated to decrease from 80% to 30% at 0.15 sec in order to test the effect of the proposed controller with different SOC levels. Figs. 19 (a) and (b) are showing the SOC of group one and group two, respectively. In case of the battery discharging, the SOC difference between the two groups are resulting in a lower power reference on group one (lower SOC) than on group two (higher SOC) to save battery group one from the over discharged situation as shown in Figs. 18 (a) and (b).

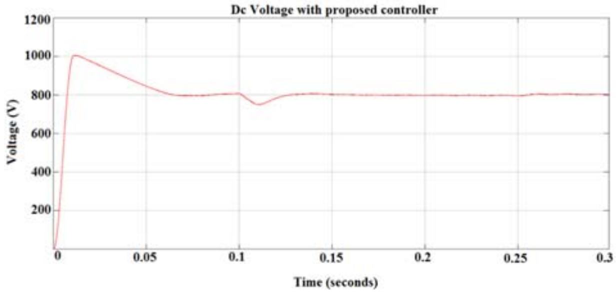
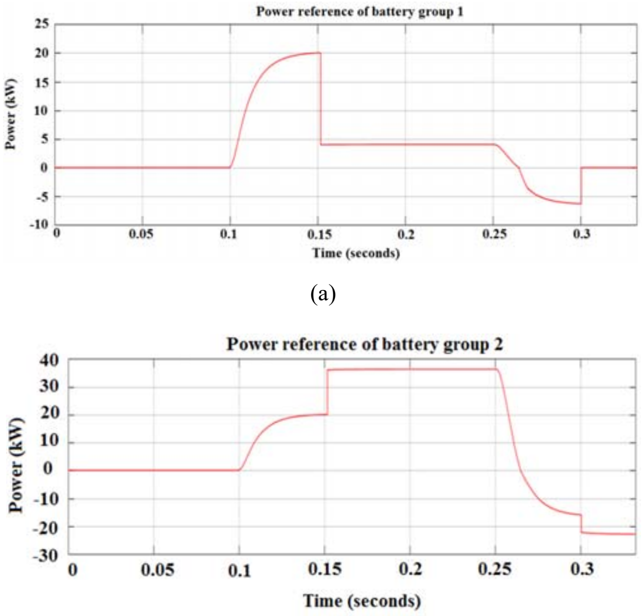


Fig. 17 DC voltage with proposed algorithm



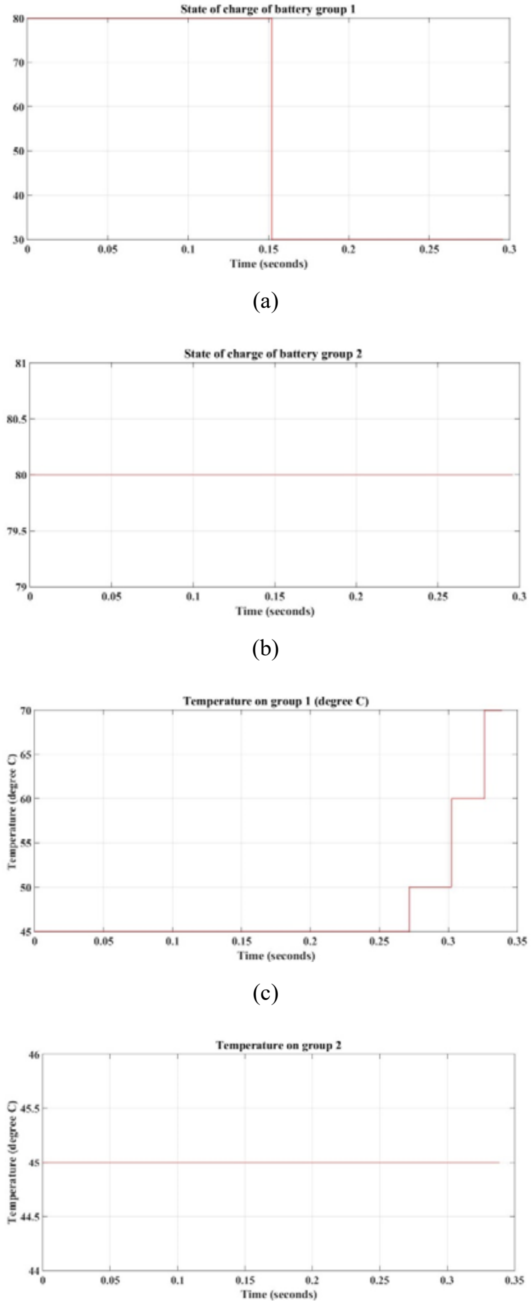
(a)

(b)

Fig. 18 Power references of group 1 and group 2

While for simulating a high temperature condition, Figs. 18 (a) and (b) are showing the reshaping of the power reference between battery group one and battery group two due to the battery temperature change at 0.3 sec. Group one is simulated to face a high temperature value reaching 70oC (critical temperature value to charge/discharge) as shown in Fig. 19 (c), while Fig. 19 (d) is showing that the temperature value of group two is constant at 45oC (normal temperature value to charge/discharge), therefore, the power of group one is zero at 0.3 sec in order to save the battery from explosion/failures due to the high temperature, while group two is charging/discharging normally.

All in all, the previous decisions are done by the controller to save the storage system from the unhealthy conditions, because when the storage system faces an extreme low SOC and extreme highs in temperature, it can affect the storage system's chemical reactions negatively and decrease the dependency of the system.



(a)

(b)

(c)

(d)

Fig. 19 Temperature and SOC changing on battery groups

V. CONCLUSION

This study proposed an approach to decrease the system power imbalance and the storage system stresses in hybrid ships. Different fuzzy logic controllers have been proposed to control a 2 pack-battery temperature for the sake of increasing the energy efficiency and support designers in the modeling process. A robust EMS has been proposed and applied for collecting the conditions from the ship equipment. In case of failiure of both packs, a second controller has been proposed to monitor and control the system regarding to the occurrence of faults that may increase the internal cell temperature and increase degradation rate as well. The results showed that the successful implementation of such controllers has led to reducing the unpredictable grid failures and contributes towards a reduced grid management cost as the storage system lifetime would ultimately increase.

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