Energy management strategies for hybrid power systems considering dynamic characteristics of power sources

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ABSTRACT Due to the rising concern of environmental problems, fuel cell hybrid power systems have been proposed to be an ideal substitution to diesel engines. However, the hybrid power system has brought many challenges, one of which is the power splitting among different power generation technologies. In this paper, a wavelet transform and fuzzy logic based energy management strategy is proposed for a fuel cell/battery/ultra-capacitor hybrid power cruiser considering their dynamic characteristics. The energy demand of the cruiser is decoupled into different frequencies by wavelet transform and distributed to different energy sources according to their dynamic characteristics. To ensure long-term reliable operation of the hybrid power system, fuzzy logic is proposed to keep the state of charges of the battery and ultra-capacitor within safe range. The proposed energy management strategy is applied to a hybrid power cruiser in MATLAB/Simulink and two cases are studied considering different initial states of charge of the energy storage system. The results show that the proposed energy management strategy enables the fuel cell to supply about 50% of the high frequency power and reduce the peak power supplied by the fuel cell by 80% - 100% when the initial state of charge of the ultra-capacitor is low, and the fuel cell supplies around 400% higher than the low peak power and 20% of the high peak power when the initial state of charge of the battery is low.

INDEX TERMS fuel cells; hybrid power systems; energy management strategies; wavelet transform; fuzzy logic

I. INTRODUCTION

WITH increasing attention to environmental protection around the world, great efforts have been made to find an alternative energy instead of using fossil energy in ship industry [1]. Fuel cell systems (FCS) have become a promising solution owing to their features including high energy efficiency and density, zero local emissions as well as low noise [2], [3]. FCS is more efficient than traditional diesel engines which convert fossil fuels to mechanical energy or electricity [4].

However, the wide usage of FCS is greatly limited by their disadvantages including incapability of energy storage, poor dynamic characteristics, short durability and great expense. Considering these disadvantages, a sole FCS may not totally satisfy the transient power demand. Consequently, FC hybrid power systems (FCHPS) comprising the FCS and an energy storage system (ESS) are usually adopted to make up these drawbacks [5]. One of the considerable merits of the FCHPS is that the FCS in the FCHPS is only responsible for base load instead of peak demand, which makes the FCHPS more cost-effective and energy-efficient than using the sole FCS [6]. If all the power demand of a boat is satisfied by a FCS without any auxiliary, the power capacity of the FCS has to be increased, and, thus, the scale, expense and hydrogen consumption will be increased significantly [7]. Besides, fuel cell systems have slow dynamic response to changes in current, voltage and load [8]. The main reason is that the internal mass transfer lags actual power requirement [9]. Practically, the FCS needs to ensure a good durability with slow load dynamics [10], because load demand fluctuations may damage the FCS stack and reduce its service life by fuel starvation, flooding, membrane drying, and pressure imbalance across
The performances of different components of the hybrid power system must be leveraged by a proper energy and power management system. Besides, the power flow between different power generation units should be coordinated properly to meet the power requirement of the boat. Many energy management strategies (EMSs) have been studied recently. These strategies can be clarified into three different types: rule-based, optimization-based and intelligent algorithm-based strategies. The first category is widely used in present hybrid cars and ships by operating the online diesel engines at their most efficient region while adopting the ESS for leverage [15], and is proved to be able to achieve a higher economic performance than traditional PID methods [16]. Tang et al. [17] proposed a wavelet and rule based EMS for a fuel cell and ultra-capacitor hybrid power ship, in which the rule-based energy management strategy is used to keep state of charges (SOC) of a UC within normal level. Another often used rule-based strategy is fuzzy logic which considers the power demand and SOC of an ESS. One typical example is the strategy proposed for a Photovoltaic/diesel/battery hybrid ship in [18], in which the power distribution can be achieved by a series of IF-THEN rules based on experience and experts’ knowledge. However, the fuzzy logic based energy management strategies do not consider the dynamic performances of energy sources, and, thus, are unable to distribute the energy demand according to the dynamic characteristics of the energy sources. A finite state machine based energy management strategy is proposed in [19] for fuel cell/battery/ultra-capacitor powered vehicles.

The optimization-based strategies include two types: instantaneous optimization and dynamic optimization. Van [20] developed a model prediction control method to minimize the cost function. Kanellos [21] developed a dynamic programming based algorithm for a hybrid wind/PV/diesel/battery system, where the energy management strategy is a multiple step procedure with respect to the state of charge. In Ref. [22], the authors propose a dynamic programming EMS for different hybrid propulsion structures. Interested readers can refer to [23] for more optimization-based energy management strategies. The intelligent algorithm-based strategies, such as deep reinforcement learning based methods, are mostly applied to hybrid electric vehicles in recent research [24], [25]. In recent works, the operation performance of fuel cells has been studied considering their dynamic performance. In [26], the authors propose an online extremum seeking algorithm based energy management strategy for a dual PEMFC/battery hybrid locomotive, which takes into consideration the dynamic performance of the PEMFC. In [27], an energy management strategy based on optimal equivalent consumption minimum strategy is proposed to identify the parameters of PEMFC in dynamic the operation process.

To sum up, these EMSs put their emphasis on the whole system but fail to capture the dynamic characteristics of individual power generation units. Although there might be some research works that consider the dynamic performance of energy sources, they are either with simple rule and hybrid power system structures, e.g., Ref. [17] or applied to electric vehicles, e.g., Ref. [28], the application of such energy management strategy in hybrid ships remains to be discussed. In this paper, an EMS is proposed for a hybrid power ship considering the dynamic response of each power source to load changes. The main contributions are summarized as follows:

- A hybrid power system that contains FCS, battery and UC is proposed for a small cruise ship. The proposed hybrid power system can achieve zero emissions;
- A wavelet transform (WT)-fuzzy logic based EMS is proposed to allocate demand requirement to each power source. The wavelet transform is used to decouple the power demand into high and low frequencies, and the low frequency power is shared by the UC and batteries due to their relatively poor dynamic performances whereas the high frequency power is supplied by the UC considering its high power density and fast response to the pulse power and fluctuations. The fuzzy logic is used to maintain the SOCs of the ESS within safe levels;
- The proposed EMS is validated on a simulated hybrid power system in MATLAB/Simulink and is proven to be able to improve the energy efficiency and extend the life cycle of fuel cell and battery by reducing their fast and sharp response.

The rest of this paper is organized as follows. In Section II, the fuel cell/battery/UC hybrid power system of a boat is introduced. The wavelet transform and fuzzy logic based EMS is then proposed in Section III, after which the simulation results are presented and analyzed in Section IV. Finally, in Section V, the whole work is concluded and future work is discussed.

II. HYBRID POWER SYSTEMS

In this part, we introduce the fuel cell hybrid power system. The propulsion system of the studied boat is illustrated in Figure 1, in which the blue lines represent information flow and the red lines stand for power flow. The boat has three energy sources connected to a common switchboard: FCS, batteries and UC. The FCS is connected to the switchboard via a unidirectional boost DC/DC converter by which the
output voltage of the FCS is increased to the standard level. The power flow from the FCS to the common bus is unidirectional since it cannot store energy. On the contrary, the battery and the UC can not only supply power to the boat but also store energy from the FCS. Therefore, the battery and the UC form the ESS of the hybrid power system and are connected to the common switchboard via bidirectional convertors. When the battery and UC supply power to the boat, their output voltages are increased to the standard voltage level by the DC/DC convertors. Conversely, when the SOC's of the battery and UC are low, they can draw energy from the common switchboard via the DC/DC convertor and get recharged by the FCS. The load of the boat include two kinds: service and propulsion load. Service load includes lighting, entertainment and electrical equipments; propulsion load drives the boat forward and is the main load of the boat. The typical application of the hybrid power system is a cruise ship in a lake or river, because the hybrid power system is featured with zero emission, and is, thus, environmentally friendly.

Generally, several kinds of fuel cells can be defined according to their electrolytes, among which the polymer electrolyte membrane fuel cell (PEMFC) is the most promising one due to its relatively small scale, light weight, and easy access of construction [29], [30]. Hence, a PEMFC is adopted our design.

FIGURE 1: Fuel cell hybrid power system considered in the present work

is the same as the common DC bus.

The energy generation and power distribution are managed by the energy management system. At each time slot, real-time power requirement, the SOC's of the ESS and the output of each energy source are collected and transmitted to the energy management system. Then, the power demand is split to each energy source by the proposed energy management strategy which is embedded in the energy management system. The main objectives of the EMS are to:

- satisfy the real-time power requirement of the boat;
- split the power requirement to energy sources properly according to their dynamic characteristics;
- protect the ESS from overcharging and over-discharging;

To achieve these goals, we propose a wavelet transform - fuzzy logic based EMS, which is introduced in the following section.

III. WAVELET-FUZZY LOGIC BASED ENERGY MANAGEMENT STRATEGIES

In the present study, the wavelet transform and fuzzy logic based EMS is proposed to decouple and split the power demand, and maintain the SOC of the ESS within normal level. Firstly, an original power signal can be decomposed into several components at different positions and scales by the proposed wavelet transform. The given power signal can be decoupled in both time and frequency domains. In the present study, we decouple the power demand signal of the hybrid power ship into two parts with different frequencies and split each part to specific energy sources according to their dynamic characteristics. Fuzzy logic is capable of solving complex nonlinear systems with the merits of desirable robustness and good real-time performance [32]. Therefore, in our proposed strategy, fuzzy logic is adopted to protect both battery and UC from overcharging or over-discharging.
The proposed WT-fuzzy logic based EMS is presented in Figure 2. In the Figure, the power signal is decoupled into three parts by the wavelet transform, i.e., the reference powers of the PEMFC, Li-ion battery and UC. But the reference power does not consider the SOCs of the ESS, so it is not the final outputs of the energy sources. The fuzzy logic takes into consideration the real-time power requirement of the hybrid power ship, the SOCs of battery and UC, and then, adjust the reference power obtained from the wavelet transform. The output of the fuzzy logic is the amount of power that should be added to the reference power of the battery and UC, i.e., $P_{\text{fuzzy-bat}}$ and $P_{\text{fuzzy-uc}}$. Thus, the final power of the Li-ion battery and UC is the sum of the reference power obtained from WT and the result from fuzzy logic, namely:

$$P_{\text{bat}} = P_{\text{ref-bat}} + P_{\text{fuzzy-bat}}$$  \hspace{1cm} (1)

$$P_{\text{uc}} = P_{\text{ref-uc}} + P_{\text{fuzzy-uc}}$$  \hspace{1cm} (2)

where $P_{\text{bat}}$ and $P_{\text{uc}}$ are the power output of the battery and UC, respectively. $P_{\text{ref-bat}}$ and $P_{\text{ref-uc}}$ stand for the reference power of the battery and the UC obtained from wavelet transform, respectively. $P_{\text{fuzzy-bat}}$ and $P_{\text{fuzzy-uc}}$ represent the power outputs of the battery and the UC obtained from the fuzzy logic. When $P_{\text{fuzzy-bat}} < 0$, the reference power of the battery will be decreased and vice versa; when $P_{\text{fuzzy-bat}} = 0$, the output of the battery equals to the reference power from the wavelet transform.

Since the power requirement is supplied by three energy sources, the output of the PEMFC will change accordingly when the power outputs of the battery and the UC change.

The final output of the PEMFC power can be calculated as:

$$P_{\text{fc}} = P_{\text{ref-uc}} - P_{\text{fuzzy-bat}} - P_{\text{fuzzy-uc}}$$  \hspace{1cm} (3)

The strategy is introduced in the following subsections in detail.

A. WAVELET TRANSFORM

The continuous wavelet transform (CWT) is defined as:

$$\text{CWT}_{a,b} = \int_{\mathbb{R}} x(t) \Psi_{a,b}(t) \, dt = \frac{1}{\sqrt{a}} \int_{\mathbb{R}} x(t) \overline{\Psi} \left( \frac{t-b}{a} \right) \, dt$$  \hspace{1cm} (4)

where $a$ and $b$ refer to the scale and shift factors, respectively. $\Psi(t)$ is the mother wavelet function, and $\overline{\Psi}(t)$ represents its conjugate function. If it is real, then:

$$\Psi(t) = \overline{\Psi}(t)$$  \hspace{1cm} (5)

However, CWT is not proper for practical scenarios. Instead, the efficient discrete wavelet transform (DWT) is preferred. The method is to select the scale and shift factor according to the power of two, thus quantity of wavelet coefficients can be reduced [33]. Thereby, the two factors will be transformed into:

$$a = 2^j, b = k \cdot 2^j; (j, k) \in \mathbb{Z}^2$$  \hspace{1cm} (6)

The DWT is defined as:

$$\text{DWT}_{j,k} = \int_{\mathbb{R}} x(t) \overline{\Psi}_{j,k}(t) \, dt = 2^{-j/2} \int_{\mathbb{R}} x(t) \overline{\Psi}(2^{-j} \cdot t - k) \, dt$$  \hspace{1cm} (7)
The Haar wavelet is chosen as the mother wavelet in the present study because of its shortest filter length in the time domain comparing with other wavelet bases [34]. The Haar wavelet can be expressed by:

\[ \Psi(t) = \begin{cases} 
1 & t \in [0, \frac{1}{2}) \\
-1 & t \in \left[ \frac{1}{2}, 1 \right) \\
0 & \text{otherwise}
\end{cases} \]  

which is illustrated as Figure 3.

![Haar wavelet](image)

In the present study, the original power requirement signal is decoupled into two kinds according to their frequency: high transient power and average power, in which the high transient power is supplied by the UC because of its advantage in dynamic characteristics, whereas the average load is shared by the PEMFC and the Li-ion battery. To achieve this goal, we adopt a three-level Haar wavelet to decompose the power demand signal. The decomposition and reconstruction process of the three-level wavelet transform is presented in Figure 4.

After the decomposition process, the original power requirement signal is decomposed into approximate power signal \( x_0 \) and detailed power signals \( x_1, x_2 \) and \( x_3 \). The detailed power signal is characterized by high frequency, so it is supplied by UC and can be calculated by:

\[ P_{\text{detail}} = x_1 + x_2 + x_3 \]  

and the approximate power is marked by low frequency and can be calculated by:

\[ P_{\text{app}} = x_0 \]  

Therefore, in the proposed energy management strategy, the real-time UC power is:

\[ P_{\text{ref-uc}} = P_{\text{detail}} \]  

and the approximate power is shared by the PEMFC and battery:

\[ P_{\text{ref-fc}} = 0.6P_{\text{app}} \]  \hspace{1cm} \[ P_{\text{ref-bat}} = 0.4P_{\text{app}} \]  

![Membership functions](image)

**B. FUZZY LOGIC**

In the above Subsection, the power signal of the hybrid power system is decoupled into different parts and supplied by different energy sources according to their dynamic characteristics. However, another problem of the Li-ion battery and the UC is their SOCs. To ensure the continuous and reliable operation of the hybrid power system, the ESS needs to be recharged when their SOCs are relatively low and discharged when three SOCs are high. In this work, we use fuzzy logic to determine when to charge and discharge the ESS.
the condition of each input variable. Finally, the outputs of the fuzzy logic are power values that should be added to the reference powers which are obtained from wavelet transform.

The first step of the fuzzy logic is the fuzzification of input and output variables. In the present study, the input variables are $SOC_{\text{bat}}$, $SOC_{\text{uc}}$ and $P_{\text{requirement}}$. Three membership functions are considered, i.e., S, M and L, of which S represents "small", M represents requirement "medium" and L represents "large", as shown in Figure 5. The output variables of fuzzy logic are the added power values of the battery and UC, i.e., $P_{\text{fuzzy-bat}}$ and $P_{\text{fuzzy-uc}}$. Each output variable has seven membership functions, of which NB, NM and NS refer to negative big, negative medium and negative small, respectively whereas PS, PM and PB mean positive small, positive medium, and positive big, respectively. Finally, Z is the acronym of zero. The membership functions of outputs are shown in Figure 6. If the output values are positive, they will supply more power than the reference power obtained from WT; if the output values turn out to be zero, the reference power from WT will be the final power outputs; otherwise, they will provide less power than the reference power or be recharged.

After defining the membership functions of the inputs and outputs, the key problem is to design fuzzy rules. Fuzzy logic in the present study is a supplement of the WT regarding specific conditions. The rules are implemented as follows:

- When the power requirement is large, the power is supplied by all the three power sources regardless of the SOCs of the ESS;
- When the power requirement is medium, whether the power is provided by the battery or UC depends on their SOCs:
  - If the SOC of the battery is high, then most or all of the power requirement is supplied by PEMFC and Li-ion battery whereas UC only supplies little power or even is recharged.
  - If the SOC of the UC is high, the UC supplies more power than the reference power obtained from the wavelet transform and vice versa.
  - If both the SOCs of the battery and UC are low, then most of the power is supplied by the PEMFC.
- When the power requirement is small, the battery and UC supply less power than the reference power from the wavelet transform, and they will be recharged by the outputs of the FCS in most cases.

The rule surfaces of various inputs and outputs are presented in Figure 7. From Subfigures 7a and 7b, we can observe that, when the SOCs of the Li-ion battery and the UC are very small (smaller than 30%), $P_{\text{fuzzy-bat}}$ and $P_{\text{fuzzy-uc}}$ are negative, implying that they supply little power to the boat or are recharged by the FCS. With the increasing of their SOCs, the battery and the UC share more and more load demand. The two subfigures illustrate the relationship between the SOC and the added values to the reference power obtained from the wavelet transform. Similarly, the rule surfaces in Subfigures 7d and 7e show that $P_{\text{fuzzy-bat}}$ and $P_{\text{fuzzy-uc}}$ increase as the power requirement increases. It can be observed from Subfigure 7c that, when $SOC_{\text{bat}}$ is
very low and the power requirement is very small, \( P_{\text{fuzzy-bat}} \) is smaller than \(-1\), implying that the battery is recharged. With the power requirement increasing, \( P_{\text{fuzzy-bat}} \) gradually increases even though the \( \text{SOC}_{\text{bat}} \) is very small. In this case, the battery supplies little or no power to the system. With the \( \text{SOC}_{\text{bat}} \) increasing whereas \( P_{\text{requirement}} \) keeps small, \( P_{\text{fuzzy-bat}} \) increases until the FCS stops charging the battery and the battery begins to supply power to the system. With \( \text{SOC}_{\text{bat}} \) and \( P_{\text{requirement}} \) both increasing, \( P_{\text{fuzzy-bat}} \) becomes positive, and the FCS share more and more energy requirement of the boat. The same situation occurs to the relationship between the output \( P_{\text{fuzzy-uc}} \) and inputs \( \text{SOC}_{\text{uc}} \) and \( P_{\text{requirement}} \), which is illustrated in Subfigure 7f.

**IV. RESULTS ANALYSIS**

The proposed strategy is tested and verified by a simulated hybrid power system in MATLAB/Simulink platform. The models of the component of the hybrid power system are the same as those in Ref. [35]. In the present study, to evaluate the performance of the proposed EMS in maintaining the SOCs of the ESS, two cases where the initial SOCs of the Li-ion battery and the UC are different are considered:

- Case 1: the initial SOCs of the battery and UC are 90% and 60%, respectively;
- Case 2: the initial SOCs of the battery and UC are 60% and 90%, respectively.

In the first case, the initial SOC of the battery is large and the initial SOC of the UC is medium. Conversely, the initial SOC of the battery is medium and the initial SOC of the
UC is large in the second case. If the proposed fuzzy logic works well, the SOCs of both the battery and the UC will be maintained within an acceptable level (larger than 30%) in the continuous operation of the hybrid power ship.

A. WAVELET TRANSFORM RESULTS
Firstly, we look at the outputs of wavelet transform. The input of wavelet transform is the original power signal $P_{\text{requirement}}$ and the outputs are the reference power of the PEMFC, the Li-ion battery and the UC, i.e., $P_{\text{ref-fc}}$, $P_{\text{ref-bat}}$ and $P_{\text{ref-uc}}$, which are presented in Figure 8.

The original power signal, which is shown in the first subfigure in Figure 8, is part of classical power requirement pattern from a passenger ship named FCS Alsterwasser in Germany [36]. It includes several working pattern including cruising, docking, stop and sailing. It should be noticed that the load verification must consider the capacity of the hydrogen tank of the FCS and the energy capacity of the ESS to enable the ship to finish the route, e.g., from one point to another point where the hydrogen tank can be refilled. We can observe that during the docking mode, the power requirement suffers from severe fluctuation, which is hard for FCS to deal with. After the decomposition of the signal by wavelet transform, we get two kinds of power signals: high frequency signal which is split to the UC, as is shown in the last subfigure in Figure 8, and the low frequency power which is shared by the PEMFC and the Li-ion battery, as is shown in the second and third subfigures in Figure 8. It can be observed that the power curves of the FCS and batteries becomes much smooth during the docking mode, whereas the fluctuation of the reference power of UC becomes dramatic. Therefore, the original power signal is decoupled into three signals of different frequencies.

![Figure 8: Power decomposition by wavelet transform](image)

B. RESULTS ANALYSIS OF CASE 1
The comparison of the power requirement and the output power of the PEMFC, Li-ion battery and UC in Case 1 is shown in Figures 9 - 11, respectively. The red lines in Figures 9 - 11 represent the output power of the PEMFC, Li-ion battery and UC, respectively, whereas the blue lines stand for the power requirement. The SOCs of the ESS are presented in Figure 12, in which the green line stands for the SOC of the battery whose initial value is 90%, and the blue one stands for the SOC of the UC whose initial value is 60%.

As can be seen in Figures 9 - 11, when the power requirement fluctuation is very small, i.e., at the period of 0 - 90s, 140 - 150s and 180 - 350s, the power requirement is shared by the PEMFC and the Li-ion battery, whereas the UC does not supply power to the system. It’s because that the UC is only responsible for high transient power and the SOC of the Li-ion battery is relatively high. When the boat is at the docking operation mode, i.e., 90 - 140s, the power requirement suffers from dramatic fluctuations, and we can see that, the output power of the PEMFC fluctuates slower than the power requirement. Besides, the PEMFC supplies little power at the peak power periods whereas most of the power requirement is satisfied by the Li-ion battery and the UC. Specifically, the PEMFC supplies about 50% of the high frequency power and the proposed EMS can reduce the peak power supplied by the FCS by 80% - 100%, which can be seen in Figure 9. Besides, the frequency of the output power of the UC is higher during the docking mode than that of the PEMFC and the Li-ion battery.

From Figure 12, we can see that the initial value of the SOC of the Li-ion battery starts from 90%, and, then, gradually drops within an acceptable range. In Figure 10, we can see that when the power requirement curve becomes steady after around 200s, the output power of the battery gradually decreases and the output power of the PEMFC increases accordingly since the $SOC_{\text{bat}}$ in Figure 12 decrease gradually. It can be noticed that the initial value of $SOC_{\text{uc}}$ in Figure 12 is 60% and the UC is recharged at the beginning of the working cycle until the $SOC_{\text{uc}}$ keeps stable at 75%. Then, at the docking mode, the UC quickly charges and discharges and finally keeps its SOC at the level of 75% when the power requirement curve is stable. The results show that the

![Figure 9: Comparison of power requirement and FCS output in Case 1](image)
Figures 13 - 16 show the simulation results of Case 2. Similar to the results in Case 1, the PEMFC and the Li-ion battery satisfy the main energy requirement whereas the UC satisfies the transient power when the power requirement curve is smooth. Compared with the outputs of the PEMFC and the Li-ion battery in Case 1 (see Figures 9 and 10), the PEMFC provides more power whereas the Li-ion battery provides less power in Case 2 due to the lower initial SOC value of the battery. Therefore, the SOC of the battery does not change much and is kept between 50% and 60%, as is shown in Figure 16. During around 90 to 170 s, when the cruiser suffers from high frequency load fluctuations, the FCS supplies around 400% higher than the low peak power and about 20% of the high peak power, making the output of the FCS smooth. Besides, the battery is recharged in this time period since the power requirement is relatively small and the proposed strategy can protect the Li-ion battery from over-discharging.

C. RESULTS ANALYSIS OF CASE 2

Figures 10 - 13 show the comparison of power requirement and battery output in Case 1 and Case 2, respectively.
the UC supplies most of the peak power. The initial value of $SOC_{uc}$ is 90% and then decreases slowly. During the docking mode, the UC is discharged and recharged alternatively and finally keeps stable at the level of 75%. The simulation results in the two cases show that the proposed EMS can split the power requirement to different energy sources according to their dynamic characteristics and keep the SOCs of the ESS at safe level.

D. POWER SOURCES OPERATING STRESS ANALYSIS

Power fluctuation is a key factor that influences the performance of power sources [37]. Inspired by Ref. [38], we present the operating stress of power sources in both Case 1 and Case 2 in Figures 17 - 22.

From Figures 17 - 19, we can observe that, in Case 1, the power fluctuation of fuel cells and batteries is mainly distributed within [-200, 200] whereas the power fluctuation of UC is distributed within [-600, 800], which indicates that the operating stress of fuel cells and batteries is lower than that of UC. The results are similar in the results of Case 2, as presented in Figures 20 - 22. The results show that the proposed energy management strategy can reduce the operating stress of fuel cells and batteries and assign the high frequency power to UC. Furthermore, it can be seen that, comparing with the results in [38], the proposed EMS in the present study can achieve a similar performance even though the fuel cell can work in a wider range in this paper.

FIGURE 15: Comparison of power requirement and UC output in Case 2

FIGURE 16: SOC of the ESS in Case 2

FIGURE 17: Power fluctuation of fuel cells in Case 1

FIGURE 18: Power fluctuation of batteries in Case 1

FIGURE 19: Power fluctuation of UC in Case 1
V. CONCLUSIONS AND FUTURE WORKS

This paper proposed a wavelet transform-fuzzy logic based EMS for a hybrid cruiser. Firstly, the high transient power requirement is decomposed into different frequencies and split to different power sources according to their dynamic performance. Then, fuzzy logic is adopted to maintain the SOC of the ESS within acceptable limits. In order to verify the proposed EMS, we study two cases where different initial SOCs of the ESS are considered. The proposed EMS is validated via a fuel cell/battery/ultra-capacitor hybrid power system in MATLAB/Simulink. The simulation results show that, when the initial SOC of the battery is high whereas that of UC is relatively low, the proposed EMS enables the PEMFC to supply about 50% of the high frequency power and reduces the peak power supplied by the FCS by 80% - 100%. On the other hand, when the initial SOC of the battery is relatively low whereas that of UC is high, the proposed EMS enables the FCS supply around 400% higher than the low peak power and 20% of the high peak power, making the output of the FCS smooth. Besides, the proposed EMS can keep the SOCs of the ESS within 50% - 80%, showing that the proposed strategy is capable of dealing with power supply under various operation conditions.

In the present work, we suppose that the power requirement is known. However, the power demand of a ship might face many uncertainties, such as the change of the sailing environment, and thus, difficult to predict. Therefore, in future works, we will consider a robust energy management strategy that considers the energy requirement uncertainty.

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REFERENCES

[1] P. Pan, Y. Sun, C. Yuan, X. Yan, and X. Tang, “Research progress on ship power systems integrated with new energy sources: A review,” Renewable and Sustainable Energy Reviews, vol. 144, p. 111048, 2021.

[2] K. Ou, W.-W. Yuan, and Y.-B. Kim, “Development of optimal energy management for a residential fuel cell hybrid power system with heat recovery,” Energy, vol. 219, p. 119499, 2021.

[3] K. Ettihir, L. Boulon, and K. Agbossou, “Optimization-based energy management strategy for a fuel cell/battery hybrid power system,” Applied Energy, vol. 163, pp. 142–153, 2016.

[4] X. Lü, Y. Wu, J. Lian, Y. Zhang, C. Chen, P. Wang, and L. Meng, “Energy management of hybrid electric vehicles: A review of energy optimization of fuel cell hybrid power system based on genetic algorithm,” Energy Conversion and Management, vol. 205, p. 112474, 2020.

[5] H. S. Das, C. W. Tan, and A. Yatim, “Fuel cell hybrid electric vehicles: A review on power conditioning units and topologies,” Renewable and Sustainable Energy Reviews, vol. 76, pp. 268–291, 2017.

[6] N. Sulaiman, M. Hannan, A. Mohamed, P. J. Ker, E. Majlan, and W. W. Daud, “Optimization of energy management system for fuel-cell hybrid electric vehicles: Issues and recommendations,” Applied energy, vol. 228, pp. 2061–2079, 2018.
M. Okumaditya, “Size optimization of a hybrid photovoltaic/fuel cell grid connected power system including hydrogen storage,” International Journal of Hydrogen Energy, vol. 46, no. 59, pp. 30539–30546, 2021.

H. Araghian, I. Ahmad, N. Ali, M. F. Munir, S. Khan, and A. Araghian, “Nonlinear controller analysis of fuel cell–battery–ultracapacitor-based hybrid energy storage systems in electric vehicles,” Arabian Journal for Science and Engineering, vol. 43, no. 6, pp. 3123–3133, 2018.

T. Zeng, C. Zhang, A. Zhou, Q. Wu, C. Deng, S. H. Chan, J. Chen, and A. M. Foley, “Enhancing reactant mass transfer inside fuel cells to improve dynamic performance via intelligent hydrogen pressure control,” Energy, vol. 230, p. 120620, 2021.

X. Li, Z. Shang, F. Peng, L. Li, Y. Zhao, and Z. Liu, “Increment-oriented online power distribution strategy for multi-stack proton exchange membrane fuel cell systems aimed at collaborative performance enhancement,” Journal of Power Sources, vol. 512, p. 230512, 2021.

T. Lochen, L. Hallitzky, M. Perchtalner, M. Obermaier, J. Sabawa, S. Enz, and A. S. Bandarenka, “Local degradation effects in automotive size membrane electrode assemblies under realistic operating conditions,” Applied Energy, vol. 260, p. 114291, 2020.

S. Acha, N. Le Brun, M. Damaskou, T. C. Fubara, V. Mulgundmath, C. N. Markides, and N. Shah, “Fuel cells as combined heat and power systems in commercial buildings: A case study in the food-retail sector,” Energy, vol. 206, p. 118046, 2020.

Y. Wang, S. J. Moura, S. G. Advani, and A. K. Prasad, “Power management system for a fuel cell/battery hybrid vehicle incorporating fuel cell and battery degradation,” International Journal of Hydrogen Energy, vol. 44, no. 16, pp. 8479–8492, 2019.

C. Nuchturee, T. Li, and H. Xia, “Energy efficiency of integrated electric propulsion for ships—a review,” Renewable and Sustainable Energy Reviews, vol. 134, p. 110145, 2020.

M. U. Muttarraf, Y. Terriche, K. A. K. Niazi, J. C. Vasquez, and J. M. Guerrero, “Energy storage systems for shipboard microgrids—a review,” Energies, vol. 11, no. 12, p. 3492, 2018.

Y. Wang, Z. Sun, X. Li, X. Yang, and Z. Chen, "A comparative study of power allocation strategies used in fuel cell and ultracapacitor hybrid systems," Energy, vol. 189, p. 116142, 2019.

T. Tang, E. Zio, Y. Yuan, J. Zhao, and X. Yan, "The energy management and optimization strategy for fuel cell hybrid ships," in 2017 2nd International Conference on System Reliability and Safety (ICRS), pp. 277–281, IEEE, 2017.

Y. Yuan, T. Zhang, B. Shen, X. Yan, and T. Long, “A fuzzy logic energy management strategy for a photovoltaic/diesel/battery hybrid ship based on experimental database,” Energies, vol. 11, no. 9, p. 2211, 2018.

Y. Wang, Z. Sun, and Z. Chen, “Energy management strategy for battery/ultracapacitor/fuel cell hybrid source vehicles based on finite state machine,” Applied energy, vol. 254, p. 113707, 2019.

T. Van Vu, D. Gonsoulin, F. Diaz, C. S. Edrington, and T. El-Meziani, “Predictive control for energy management in ship power systems under high-power ramp rate loads,” IEEE Transactions on Energy Conversion, vol. 32, no. 2, pp. 788–797, 2017.

L. N. An and T. Q. Tuan, “Dynamic programming for optimal energy management of hybrid wind–pv–diesel–battery,” Energies, vol. 11, no. 11, p. 3039, 2018.

Y. Wang, X. Li, L. Wang, and Z. Sun, “Multiple-grained velocity prediction and energy management strategy for hybrid propulsion systems,” Journal of Energy Storage, vol. 26, p. 100950, 2019.

P. Xie, J. M. Guerrero, S. Tan, N. Bazmohammadi, J. C. Vasquez, M. Mehrzadi, and Y. Al-Turki, “Optimization-based power and energy management system in shipboard microgrid: A review,” IEEE Systems Journal, 2021.

H. Sun, Z. Fu, F. Tao, L. Zhu, and P. Si, “Data-driven reinforcement-learning-based hierarchical energy management strategy for fuel cell/battery/ultracapacitor hybrid electric vehicles,” Journal of Power Sources, vol. 455, p. 227964, 2020.

B. Xu, X. Hu, X. Tang, X. Lin, H. Li, D. Rathod, and Z. Filipi, “Ensemble reinforcement learning-based supervisory control of hybrid electric vehicle for fuel economy improvement,” IEEE Transactions on Transportation Electrification, vol. 6, no. 2, pp. 717–727, 2020.

T. Wang, Q. Li, L. Yin, W. Chen, E. Breaz, and F. Gao, “Hierarchical power allocation method based on online extremum seeking algorithm for dual-pemfc/battery hybrid locomotive,” IEEE Transactions on Vehicular Technology, 2021.

T. Wang, Q. Li, X. Wang, Y. Qiu, M. Liu, X. Meng, J. Li, and W. Chen, “An optimized energy management strategy for fuel cell hybrid power system based on maximum efficiency range identification,” Journal of Power Sources, vol. 445, p. 227333, 2020.

O. Erdinc, B. Vural, and M. Uzunoglu, “A wavelet-fuzzy logic based energy management strategy for a fuel cell/battery/ultra-capacitor hybrid vehicular power system,” Journal of Power sources, vol. 194, no. 1, pp. 369–380, 2009.

P. Thounthong, S. Rael, and B. Davat, “Energy management of fuel cell/battery/supercapacitor hybrid power source for vehicle applications,” Journal of Power Sources, vol. 193, no. 1, pp. 376–385, 2009.

S. Njoua Motapon, L.-A. Dessaint, S. Liscouret-Hanke, and C. Lavoie, “Simulation of a fuel cell hybrid energy management system for more electric aircraft,” 2011.

N. Nitta, F. Wu, J. T. Lee, and G. Yushin, “Li-ion battery materials: present and future,” Materials today, vol. 18, no. 5, pp. 252–264, 2015.

L. Ibarra and C. Webb, “Advantages of fuzzy control while dealing with complex/unknown model dynamics: A quadcopter example,” New Applications of Artificial Intelligence, pp. 93–121, 2016.

S. Dusmez and A. Khaligh, “A supervisory power-splitting approach for a new ultracapacitor–battery vehicle deploying two propulsion machines,” IEEE Transactions on Industrial Informatics, vol. 10, no. 3, pp. 1960–1971, 2014.

M. Uzunoglu and M. Alam, “Modeling and analysis of an fc/uc hybrid vehicular power system using a novel-wavelet-based load sharing algorithm,” IEEE Transactions on Energy Conversion, vol. 23, no. 1, pp. 263–272, 2008.

S. Njoua Motapon, Design and simulation of a fuel cell hybrid energy management system for a more electric aircraft: evaluation of energy management schemes. PhD thesis, École de technologie supérieure, 2013.

A. M. Bassam, A. B. Phillips, S. R. Turnock, and P. A. Wilson, “Development of a multi-scheme energy management strategy for a hybrid fuel cell driven passenger ship,” International Journal of Hydrogen Energy, vol. 42, no. 1, pp. 623–635, 2017.

T. Wang, Q. Li, Y. Qiu, L. Yin, L. Liu, and W. Chen, “Efficiency extreme point tracking strategy based on fisf online identification for pemfc system,” IEEE Transactions on Energy Conversion, vol. 34, no. 2, pp. 952–963, 2018.

Q. Li, T. Wang, S. Li, W. Chen, H. Liu, E. Breaz, and F. Gao, “Online extremum seeking-based optimized energy management strategy for hybrid electric tram considering fuel cell degradation,” Applied Energy, vol. 285, p. 116505, 2021.

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