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Optimal energy management for fuel saving in the fuel cell hybrid excavator

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***Abstract*—This paper describes an optimal energy management approach for a fuel cell hybrid excavator (FCHE) powered by a fuel cell (FC) system and energy storage devices composed of a Li-ion battery pack and supercapacitor bank. In order to meet the fuel-saving demand, an equivalent consumption minimization strategy (ECMS) is proposed, which not only guarantees the load power adaptation but also minimizes the hydrogen consumption and improves the operating efficiency of the fuel cell stack. Comparative simulations are carried out to verify the effectiveness and feasibility of the proposed ECMS methodology under different working conditions.**

Keywords—Fuel cell excavator, power management, fuel saving, optimization.

I. Introduction

Hybrid excavators have recently become popular in a variety of civil and industrial applications, offering numerous benefits such as reduced fossil fuel consumption, lowered greenhouse gas emissions, and less damage to the environment. Among them, FCHE is emerging as an eco-friendly system in the strategy of using renewable energy sources not only for construction machinery but also for electric vehicles [1]. In the FCHE configuration, the primary electric energy is generated by using the FC system that runs on hydrogen fuel. Due to the slow dynamic response of the fuel cell system, FCHE integrates energy storage devices (ESDs) such as battery (BAT), supercapacitor (SC), or both BAT and SC to assist the FC dynamic for load power adaptation and extend the lifetime of fuel cell system under different working conditions [2]. Based on the high dynamic response, the SC serves to deliver the peak power, while the BAT is used as the secondary energy source to deal with the dynamic limitation of the FC system. Based on this flexible structure, some hybrid construction machinery models have been developed with the structure of FC/BAT [3], FC/SC [4], or FC/BAT/SC [5, 6].

In order to guarantee the hybrid system performance, energy management strategies (EMSs) are designed for load power adaptation, power distribution between FC system and ESDs, and optimal requirements such as fuel economy, FC stack efficiency improvements, and so on. For the FCHE, rule-based (RB) strategies and optimization-based (OB) strategies are the two types of EMSs that have been implemented. RB strategies are designed based on the predetermined rules that use the previous information or heuristics to define the power distribution for each power source. It is difficult to satisfy the continuously repeatable switch of system behaviors, as well as the fluctuation of load conditions in different real-world working cycles, which can affect the parameters of these rules. Thus, these methods face several obstacles in terms of ensuring the system's performance and achieving optimal requirements for FCHE. To overcome this limitation, OB strategies are developed to enhance the system qualification. Dynamic programming (DP)-based EMS was used to minimize hydrogen consumption and optimize the component sizing of an FC-BAT excavator [7] and improve the fuel cell efficiency of an FC-SC excavator [8]. An optimization method based on Pontryagin's minimum principle (PMP) [9] was proposed to meet the powertrain demand, minimize hydrogen consumption, and improve economic problems for the configuration of the FC-SC hybrid excavator. However, the DP and PMP methods, on the other hand, are considered offline optimization strategies with limitations for online optimal requirements. In order to improve system performance in real-time, the multi-objective optimal model predictive control (MPC)-based EMS was applied to not only minimize hydrogen consumption and achieve economic requirements but also maintain the SOC of ESDs for FC-BAT excavator [10] and FC-SC excavator [11, 12]. An MPC also faces challenges due to the critical condition for building an accurate model and the large computation required to solve optimization problems in each sampling time. Being a most common optimization technique and easy to operate in real-time, an equivalent consumption minimization strategy (ECMS) is utilized to achieve the optimal requirements for FCHE by designing a cost function, which consists of equivalent factors of hydrogen consumption and equivalent fuel consumption of other power sources.

Motivated by the aforementioned analyses, in this paper, an optimal energy management technique is developed based on an ECMS to satisfy the load power adaptation, optimize power distribution between the FC and ESDs, improve FC stack efficiency, and reduce hydrogen consumption for fuel-saving demand of an FCHE. A cost function with a multi-objective optimal strategy is proposed by transforming the energy consumption of ESDs into equivalent hydrogen consumption and then minimizing the total equivalent hydrogen consumption from the FC system and ESDs to ensure the maximum fuel economy. Finally, comparative simulations are carried out to verify the effectiveness of the proposed strategy with two other methods.

II. Hybrid Excavator Structure

A. Power-train structure

Fig. 1 shows the structure of the FCHE. This system is composed of the following elements: an FC system, a Li-ion

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BAT, an SC bank, a unidirectional DC/DC converter, two bidirectional DC/DC converters, the traction motor, and the energy management controller. In this system, the FC system serves as a primary power source while ESDs (BAT and SC) are utilized to compensate for the lacking power in the initial phase, the transient period, peak power demands, or regenerative energy due to a high energy density and high power density. This configuration offers a versatile mechanism for controlling the DC bus voltage, enhancing working performance, and achieving fuel economy for the FCHE system.

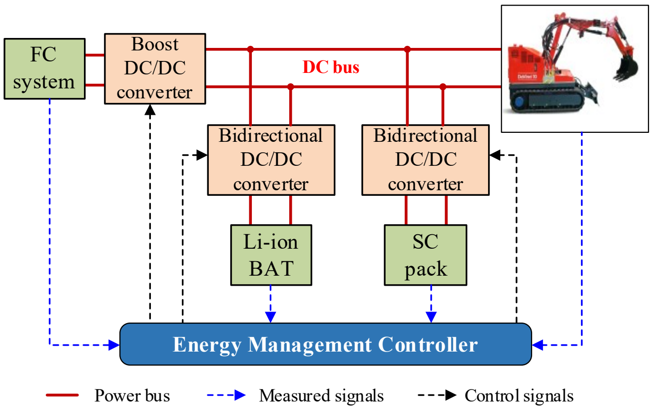

Fig. 1 Structure of fuel cell hybrid excavator.

B. Power plant model

The equivalent circuit models of FC stack and ESDs are detailed in [13]. For the FC system, the total output voltage and power are given by:

$$V_{FC} = NV_{ce} \tag{1}$$

$$P_{FC} = \eta_{FC} V_{FC} I_{FC} \tag{2}$$

where V_{FC} is the FC stack output voltage (V), V_{ce} is the cell output voltage (V), N is the total number of cells, P_{FC} is the PEMFC stack power (W), η_{FC} is the FC stack efficiency (%), and I_{FC} is the FC stack output current (A).

The hydrogen consumption is calculated as follows:

$$m_{H_2} = \int_0^t \frac{P_{FC}(t)}{\eta_{FC}\rho_{H_2}} dt \tag{3}$$

where m_{H_2} denotes the hydrogen consumption (g), ρ_{H_2} is the energy density of hydrogen chemical (MJ/kg).

Based on technical input parameters, the predetermined polarization curves of voltage-current (U-I) and power-current (P-I) are defined to illustrate the FC stack characteristics as shown in [14].

For the BAT, the output voltage and SOC can be obtained as follows:

$$V_{BAT} = E_b - R_{ib} I_{BAT} \tag{4}$$

$$SOC_{BAT}(t) = SOC_{BAT}(t_0) - \frac{1}{Q_{BAT}} \int_{t_0}^{t} I_{BAT}(\tau) d\tau \tag{5}$$

where R_{ib} is the BAT internal resistance (Ω), E_b is the nonlinear voltage (V) that equals E_{dis} in discharge mode and equals E_{ch} in charge mode as defined in [13], Q_{BAT} is the maximum BAT capacity (Ah), t is the present time, and t_0 is the initial time.

For the SC pack, the output voltage and SOC can be calculated as follows:

$$V_{SC} = \frac{N_s Q_{SC}}{N_p C} - R_{isc} I_{SC} \tag{6}$$

$$SOC_{SC}(t) = SOC_{SC}(t_0) - \frac{1}{Q_{SC}} \int_{t_0}^{t} I_{SC}(\tau) d\tau \tag{7}$$

where I_{SC} is the SC output current (A), R_{isc} is the SC module resistance (Ω), Q_{SC} is the total electric charge (C), C is the capacitance of an electric double-layer capacitors cell (F), N_s denotes the cells in series, N_p presents cells in parallel.

In order to control the power flows in the FCHE, DC/DC converters are designed with two types of boost converter and bidirectional converter. These converters are utilized to connect the FC, BAT, and SC with a DC bus that supplies the required power to the load demand. The structure of these converters is described in [15]. Duty cycles used to control the converter can be calculated by:

$$D_{buck} = \frac{V_{out}}{V_{in\_max}\eta_{buck}} \tag{8}$$

$$D_{boost} = 1 - \frac{V_{in\_min}\eta_{boost}}{V_{out}} \tag{9}$$

where D_{boost}, D_{buck} are the duty cycle of boost and buck mode (%), V_{in_min}, V_{in_max}, and V_{out} are the minimum, maximum input voltage and output voltage (V) of the converter, respectively. η_{buck} and η_{boost} are the efficiencies of the converter which are estimated to equal 90% for buck mode and 80 – 90% for boost mode, respectively.

III. ECMS-BASED OPTIMIZATION

In this work, the proposed EMS is designed based on the load power and SOC of ESDs to satisfy the load power adaptation, determine the power-sharing of energy sources, and guarantee the fuel economy of FCHE. Fig. 2 presents the overall structure of the proposed control strategy.

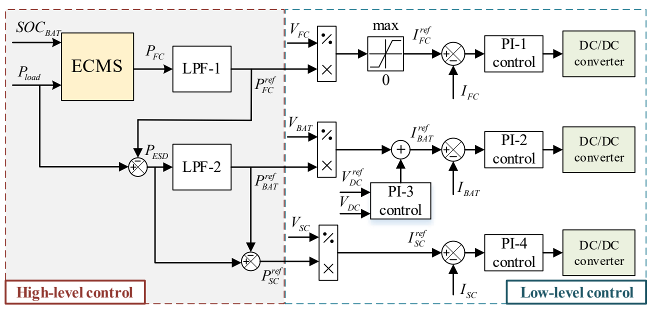

Fig. 2. The proposed control strategy.

The essence of the optimization-based EMS is instantaneous control the power flow from FC system and ESDs to adapt load demand while ensuring optimal requirements such as minimizing fuel consumption, increasing FC stack efficiency, or keeping the

SOC level of ESDs. In general terms, the cost function and constraints of optimal criterion can be defined as follows:

$$\begin{gathered} J_t = J_t\left(P_{FC}(t), P_{ESD}(t)\right) \\ \left\{P_{FC}^{opt}(t), P_{ESD}^{opt}(t)\right\} = \arg \min_{\{P_{FC}(t), P_{ESD}(t)\}} J_t \end{gathered} \tag{10}$$

$$\text{subject to: } \begin{cases} P_{req}(t) = P_{FC}(t) + P_{ESD}(t) \\ SOC_{ESD}^{\min} < SOC_{ESD}(t) < SOC_{ESD}^{\max} \\ 0 \le P_{FC}(t) \le P_{FC}^{\max} \\ P_{ESD}^{\min} \le P_{ESD}(t) \le P_{ESD}^{\max} \end{cases}$$

where J_t is the cost function at time t, SOC_{ESD} is the equivalent SOC of ESDs consisting of BAT and SC (%), P_{req}, P_{FC}, and P_{ESD} are the load power demand, FC power, and ESD power (W), respectively.

Based on the optimal objectives, an ECMS was employed to define the optimal PEMFC power. The instantaneous cost function is the sum of hydrogen consumption and equivalent fuel consumption of BAT and SC that can be given as follows:

$$J_t = \dot{m}_{H_2} P_{FC}(t) + \alpha \dot{m}_{ESD} P_{ESD}(t) \tag{11}$$

$$P_{ESD} = P_{BAT} + P_{SC} \tag{12}$$

$$\dot{m}_{ESD} = \dot{m}_{BAT} + \dot{m}_{SC} \tag{13}$$

where P_{BAT} and P_{SC} are the BAT and SC power (W), respectively; α is the penalty coefficient, $\dot{m}_{ESD}$ is the equivalent fuel consumption of ESD, $\dot{m}_{BAT}$ and $\dot{m}_{SC}$ are the equivalent consumption of BAT and SC, respectively. In the hybrid system, the SC is used to generate the peak power that FC and BAT can not compensate or absorb in a short time. The SC equivalent consumption can be neglected due to its minimum contribution [16]. Thus, the cost function (11) can be rewritten by:

$$J_t = \dot{m}_{H_2} P_{FC}(t) + \alpha \dot{m}_{BAT} P_{BAT}(t) \tag{14}$$

The optimization problem of fuel consumption is defined by

$$P_{FC} = \min\left(\dot{m}_{H_2} + \alpha \dot{m}_{BAT}\right) \tag{15}$$

The BAT equivalent consumption is computed as

$$\dot{m}_{BAT} = P_{BAT} \sigma \frac{\dot{m}_{H_2,avg}}{P_{FC,avg}} \tag{16}$$

where $\dot{m}_{H_2,avg}$ and $P_{FC,avg}$ are the average hydrogen consumption and average FC power, respectively; and σ is the BAT factor defined based on the charged and discharged coefficients as

$$\sigma = \begin{cases} \dfrac{1}{\gamma_{chg,avg} \gamma_{dis}} & P_{BAT} \ge 0 \\ \gamma_{chg} \gamma_{dis,avg} & P_{BAT} < 0 \end{cases} \tag{17}$$

where γ_{chg}, $\gamma_{chg,avg}$, γ_{dis}, and $\gamma_{dis,avg}$ are the charged, average charged, discharged, and average discharged coefficients of a BAT equivalent consumption, respectively.

The charged and discharged coefficients are specified by:

$$\gamma_{chg/dis} = \begin{cases} 0.5\left(1 + \sqrt{1 - \dfrac{4R_{dis} P_{BAT}}{V_{OC}^2}}\right) & P_{BAT} \ge 0 \\ 2/\left(1 + \sqrt{1 - \dfrac{4R_{chg} P_{aux}}{V_{OC}^2}}\right) & P_{BAT} < 0 \end{cases} \tag{18}$$

where R_{chg} and R_{dis} are the resistances of BAT charging and discharging (Ω), and V_{OC} is the BAT open circuit voltage (V).

The penalty coefficients α can be expressed by:

$$\alpha = 1 - 2\mu \frac{SOC_{BAT} - 0.5\left(SOC_{BAT}^{\max} + SOC_{BAT}^{\min}\right)}{SOC_{BAT}^{\max} + SOC_{BAT}^{\min}} \tag{19}$$

with boundary conditions as

$$P_{BAT}^{\min} \le P_{BAT} \le P_{BAT}^{\max} \tag{20}$$

$$SOC_{BAT}^{\min} < SOC_{BAT}(t) < SOC_{BAT}^{\max} \tag{21}$$

$$0 \le \alpha \le 100 \tag{22}$$

where μ is a balance coefficient (<0.6), $SOC_{BAT}^{\min}$ and $SOC_{BAT}^{\max}$ are the minimum and maximum BAT SOC (%), respectively; $P_{BAT}^{\min}$ and $P_{BAT}^{\max}$ are the minimum and maximum BAT power (W), respectively.

The reference optimal FC power is obtained in real time by solving the above numerical constraint optimization problem based on a quadratic programming method. This FC power is used to calculate the reference power of the PEMFC, BAT, and SC as follows:

$$P_{FC}^{ref} = G_1(s) P_{FC} \tag{23}$$

$$P_{ESD} = P_{load} - P_{FC}^{ref} \tag{24}$$

$$P_{BAT}^{ref} = G_2(s).P_{ESD} \tag{25}$$

$$P_{SC}^{ref} = P_{ESD} - P_{BAT}^{ref} \tag{26}$$

where P_{FC}^{ref}, P_{BAT}^{ref}, and P_{SC}^{ref} are reference powers of the FC, BAT, and SC, respectively. P_{load} is load power demand (W). $G_1(s)$ and $G_2(s)$ are the function of the low pass filters (LPF-1 and LPF-2) as presented in [17], respectively.

As a result, the reference powers of PEMFC, BAT, and SC as calculated above are used in the low-level control to define the reference currents of power sources, which generated the PWM signals to control DC/DC converters based on PI controllers. The suitable controller gains are inherited from [18] that guarantee the load power adaptation and stability of DC bus voltage in FCHE.

IV. SIMULATION RESULTS

In this section, a numerical simulation is conducted to evaluate the effectiveness of the proposed ECMS optimization strategy in comparison with two other methods of rule-based EMS in [15] and fuzzy-based EMS in [13]. In addition, the modeling of the FCHE has deployed in Matlab/Simulink 2021b environment with a sampling time for displaying simulation results at 0.05 ms. The reasonable parameters of energy sources (FC, BAT, SC), the traction motor parameters, and a specific driving cycle of FCHE are inherited from [6].

Firstly, the load power adaptation of three EMSs is presented in Fig. 3, with a continuous black line representing the reference load power demand, a dashed-dot green line indicating the power adaptation of rule-based EMS (RB-EMS), a dashed-dot blue line showing the load power adaptation of fuzzy-based EMS (F-EMS), and a dashed-dot red line displaying the load power adaptation of the proposed optimization strategy (proposed-ECMS).

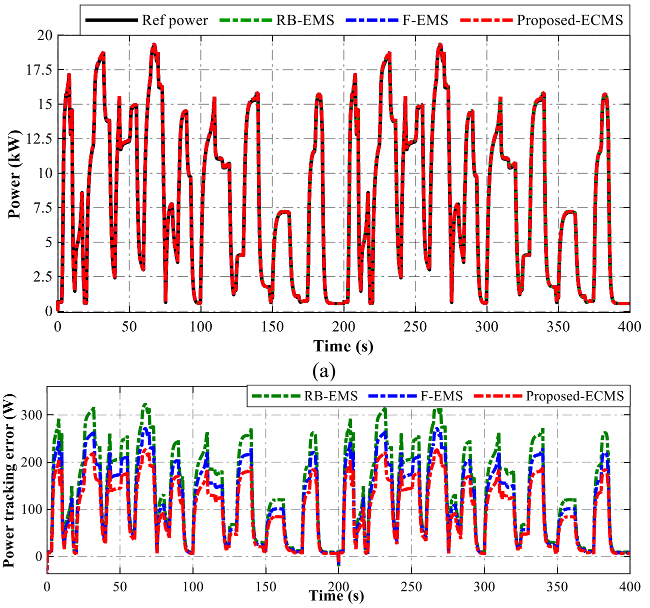

Fig. 3. Load satisfaction under three strategies.

In general, all three algorithms could satisfy the load requirement with maximum power approximated 20kW as shown in Fig. 3(a). However, it can be seen in Fig. 3(b) that the proposed strategy achieves the least power tracking error in the range of (0 → 225) W. Meanwhile, the RB-EMS and the F-EMS take insufficient powers in the range of (0 → 324) W and (0 → 271) W, respectively. This result proves that the proposed ECMS can improve the accuracy of load power adaptation under different operating conditions.

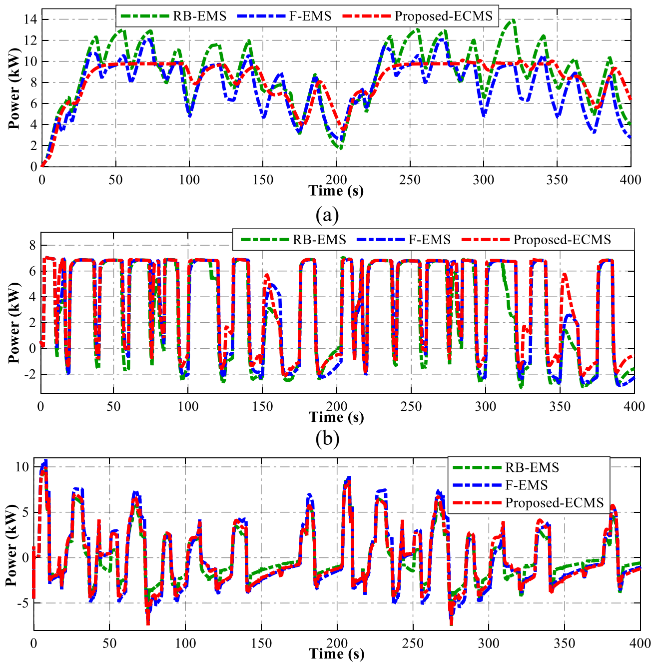

Fig. 4. The power distribution of energy sources. (a) FC. (b) BAT. (c) SC.

The power distributions of the FC, BAT, and SC in the hybrid system are shown in Fig. 4. For the FC, the proposed strategy generates the optimal power distribution at the high-efficiency region as presented in Fig. 4(a). This optimal FC power can ensure a stable adaptation for load power demand, which can improve the fuel economy and durability of the FC system. Additionally, the distribution of BAT and SC in Fig . 4(b) and (c) is employed to supplement the slow power response of the FC as well as guarantee a smooth power response to charge the redundant power from the DC bus to the BAT.

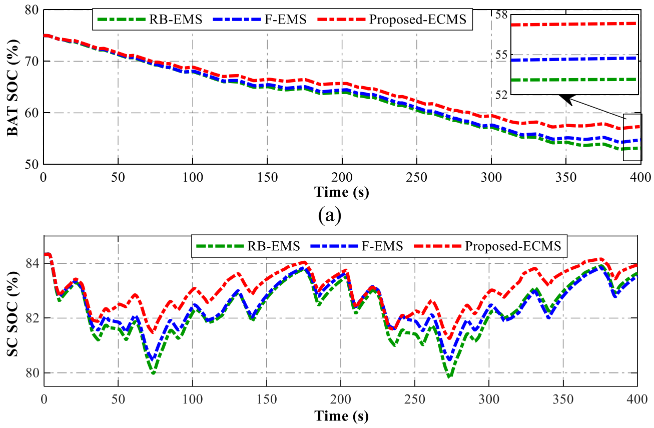

Fig. 5. The SOC status. (a) BAT SOC. (b) SC SOC.

The SOC levels of BAT and SC are depicted in Fig. 5. In detail, the BAT SOC of the three strategies varies in the range of (50 → 75)% which maintains the limitation. For the SC, the SOC level also changes in the desired value of (80 → 85)%.

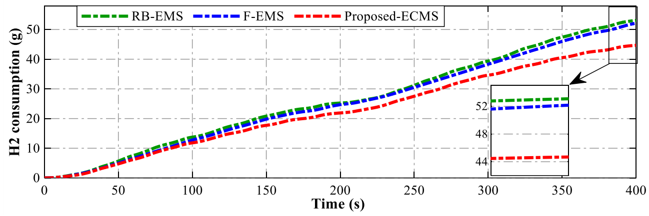

Fig. 6. The comparison of hydrogen consumption.

The hydrogen consumption of three EMSs is described in Fig. 6. Overall, the proposed ECMS has the least total hydrogen consumption. In detail, the RB-EMS and the F-EMS have a hydrogen fuel consumption of 53.1 (g) and 52.2 (g) in comparable operating conditions, respectively. In contrast, in the case of the proposed strategy, hydrogen consumption is 44.7 (g) which reduces 8.4 (g) (15.81 %) and 7.5 (g) (14.36 %) in comparison to the RB-EMS and F-EMS, respectively. This result demonstrates that the proposed optimal strategy can save the fuel economy with hydrogen consuming less than compared to other ways.

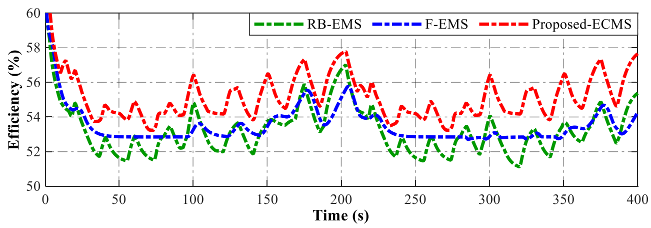

Fig. 7. The comparison of PEMFC stack efficiency of PEMFC stack.

Besides, the FC stack efficiency of three EMSs is evaluated as described in Fig. 7. It can be seen from equation (3) that the fuel consumption and stack efficiency have inverse propotional correlations. The lower the fuel consumption, the better the fuel cell stack efficiency. From the above figure, the proposed strategy achieves the highest average FC stack efficiency of over 54.5 % in comparison to the average efficiency of F-EMS with 53 % and RB-EMS with over 52 %.

V. CONCLUSION

This paper presents an optimization EMS in order to satisfy the load power demand and optimize the power distribution between the energy sources of FCHE based on the ECMS method. This optimization strategy not only maintains the load power adaptation but also reduces fuel consumption. The obtained results show that the proposed strategy achieves effectiveness and feasibility in reducing hydrogen consumption by 44.7 (g) compared to 52.2 (g) consumed fuel for F-EMS and 53.1 (g) used for RB-EMS. Consequently, this method can be considered as a premise optimization EMSs for expansion on FC hybrid electric applications with more than two power sources in the future. Furthermore, the DC bus voltage regulation and the impact of power source degradation are being further developed to enhance the optimization of energy management comprehensively.

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