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Fuzzy Logic Based Energy Management for Fuel Cell/Battery Hybrid Systems

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Abstract— **The aim of energy management of the fuel cell battery hybrid system is to minimize the energy consumption while satisfying load demands. This paper proposes an energy management method for a hybrid energy system which consists of a proton exchange membrance fuel cell, two boost converters and a lithium-ion battery pack. The goal is to guarantee a proper current of the fuel cell so that the consumption of hydrogen is minimized with constraints on power and the state of charge. The necessary conditions for the minimal hydrogen consumption is derived by using Pontryagin's maximum principle. According to this optimization method, the optimal current reference of the fuel cell can be computed analytically by iteration. Compared with solving partial differential equations with the traditional variational method, the proposed method is computationally more efficient. Moreover, by adjusting the state of charge and the load demand, we guarantee that the actual battery current can keep up with the reference value. Simulation results validate the effectiveness of the proposed energy management algorithm.**

I. INTRODUCTION

Environmental pollution has become a severe societal problem nowadays. Fuel cells (FCs) are considered as one of the most attractive power generation methods in the future [1]. FC takes fuel as input and produces electricity as output continuely, as long as fuel is supplied. Particularly, proton exchange membrane fuel cells (PEMFCs) are a type of FCs with zero emission and pollution, and low operation temperature, and thus are suitable for automotive use [2]. However, due to the frequent starting and stopping operations of vehicles, the lifetime of the fuel cell in fuel cell vehicles will be seriously reduced [3]. Thus, lithium-ion batteries are usually used as a secondary power source together with fuel cells to constitute a hybrid power system for auto-vehicles [4]. The lithium-ion battery system can (sometimes with difficulty) provide enough power to cars during periods of peak power demand such as vehicle acceleration or traveling at a high speed.

In a Fuel Cell Hybrid Electric Vehicle (FC-HEV), the conventional internal-combustion engine is replaced by the fuel cells. [5] and [6] provide a comprehensive survey of FC-HEV on their source combination, with a focus on modeling of energy management. The FC-HEV energy management and current infrastructure issues are main challenges in the future. In order to reduce the fuel consumption rate of the fuel cell, many control methods have been proposed to optimize energy management system (EMS) in [7], [8], [9], [10], [11]. The strategies in [7], [9] involve fuzzy self-organizing concepts. Genetic algorithm (GA) is also used to optimize the control parameters by off-line program [8]. An optimal control strategy based on the Pontryagin's minimum principle is presented for cases without state constraints [12]. In [12], the control objective is to minimize the hydrogen consumption, but the validity and accuracy of the control s-trategy remains to be verified. In [13], an energy management controller is designed based on the classical proportional-integral for its simplicity. However, the control performance still needs to be strengthened. Besides, an optimal strategy based on dynamic programming is presented in [12], which can reduce the computational time as well as increase the accurary.

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In recent years, many new methods are proposed to solve control problems. In [14], a two-loop framework is used to find a quasi-optimal solution of multi-objective optimization problem. The approximate Pareto surface is also presented to solve multi-objective optimization problems in [15].

Besides, in recent years, many new methods are proposed to solve control problems. Some researchers studied the energy management problem from the frequency domain. The electrochemical analysis method (EIS) [16], [17] is also proposed to analyse fuel cell models. This method simplifies fuel cells into an equivalent circuit model, which reduces the difficulty of analysing, but the mechanism of fuel cells is not known. In this paper, we use fuzzy logic control to control the output current of battery. The power distribution between fuel cell system and battery system is determined by the demand of load. Lithium-ion battery's state of charge (SOC) also needs to be taken into consideration.

This paper processes a hybrid power system, which constitutes of fuel cell and battery to supply electrical vehicle. A nonlinear control method based on the passivity principle is chosen here in order to deal with the nonlinearities existing in the whole hybrid electrical vehicle. Despite other methods passivity based control is suitable for such system and its advantages will be presented in the next sections. This paper is organized as the following manners. Section II presents the model of the hybrid energy system. Method and design of the controller are presented in Section III. Simulation results for optimizing energy management strategy are presented in Section IV. Conclusion is presented in the last Section.

II. MODEL OF HYBRID ENERGY SYSTEM

The structure of a hybrid energy system is shown in Fig. 1. In this system, the fuel cell and the lithium-ion battery pack provide electrical energy regarding the load as a hybrid power source. The mathematical model of the fuel cell and lithium-ion battery hybrid energy system are presented in this section.

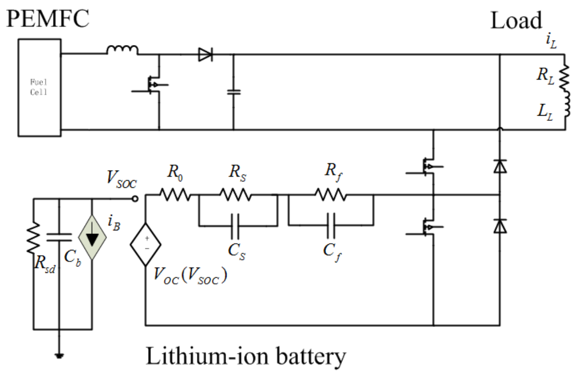

Fig. 1: Model of hybrid energy system

A. Fuel Cell Model

The fuel cell model contains a static current-voltage model and a dynamic air supply model, where the air supply model is only used for simulation. The polarzation curve of the fuel cell is provided by Sunrise Power Inc. which is shown in Fig. 2. Based on Fig. 2, when the current density(J) $> 100mA/cm^2$, the relationship between currrent density and fuel cell voltage is almost linear. Therefore, in this region, the relationship of current and voltage is given as follows:

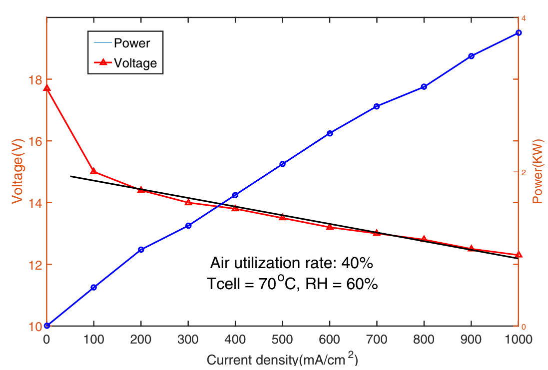

Fig. 2: Polarization curve of fuel cell stack provided by Sunrise Power Inc.

$$\begin{aligned} i_{FC} &= AJ \\ V_{FC} &= V_0 - R_{FC} i_{FC} \\ P_{FC} &= V_{FC} i_{FC} = (V_0 - R_{FC} i_{FC}) i_{FC} \end{aligned} \tag{1}$$

where A is the cell's area, V_0 is the initial voltage, V_{FC} is the output voltage of fuel cell, i_{FC} is the output current of fuel cell, P_{FC} is the output power of fuel cell, and R_{FC} is the internal resistance of fuel cell. Based on (1), we can get the output current of fuel cell as follows:

$$i_{FC} = \frac{V_0 - \sqrt{V_0^2 - 4R_{FC}P_{FC}}}{2R_{FC}} \tag{2}$$

B. Battery Model

Battery is a device that produces electricity from a chemical reaction. A comprehensive and accurate electrical model is shown in Fig. 1. On the left, a resistor-capacitor network and a current-controlled current source represents the capacity and SOC. $V_{SOC}(t)$ represents SOC of the lithium-ion battery, and $V_{SOC}(t) \in [0V, 1V]$ corresponds to $0\% - 100\%$ for the SOC. On the right, two RC networks which are similar to Thevenin-based model represent the transient response. V_s and V_f are voltages across the capacitors of RC networks. State equations of the battery model are given by [18]:

$$\begin{aligned} &\tfrac{d}{dt}V_s(t) = \tfrac{1}{C_s}(i_B(t) - \tfrac{V_s(t)}{R_s}) \\ &\tfrac{d}{dt}V_f(t) = \tfrac{1}{C_f}(i_B(t) - \tfrac{V_f(t)}{R_f}) \\ &\tfrac{d}{dt}V_{SOC}(t) = \tfrac{1}{C_b}(-i_B(t) - \tfrac{V_{SOC}(t)}{R_{sd}}) \\ &V_B(t) = V_{OC}(t) - i_B(t)R_0 - V_s(t) - V_f(t) \end{aligned} \tag{3}$$

where $i_B(t)$ is the output current of the battery. $R_0(t)$ is the internal resistance. $V_B(t)$ is output voltage of battery. $V_{OC}(t)$ is the open-circuit voltage, which changes with different SOC's level, as shown in Fig. 3. Therefore, voltage-controlled voltage source $V_{OC}(V_{SOC})$ is used to describe the relationship between the open-circuit voltage and V_{SOC}. The open-circuit voltage is usually measured as a static-state open-circuit voltage at different points of SOC. Then, the function relationship between the open-circuit voltage and V_{SOC} can be obtained by curve fitting. As shown in Fig. 3, when $V_{SOC} \in [0.2, 0.9]$, $V_{OC} = f(V_{SOC})$ is almost linear [19], [20]. Therefore, the relationship between the open-circuit voltage and V_{SOC} can be described as $V_{OC}(t) = aV_{SOC}(t) + b$.

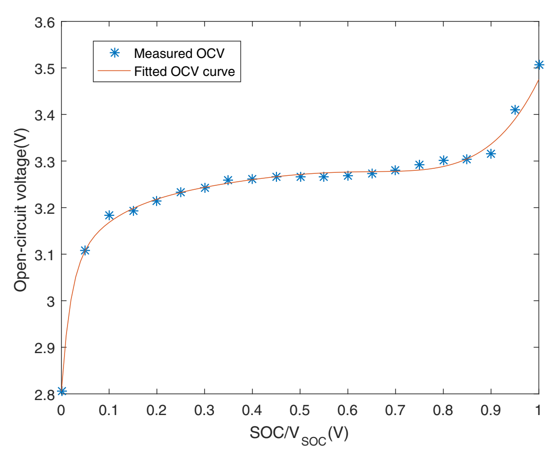

Fig. 3: The relationship between the open-circuit voltage and the Battery's SOC in [19]

C. Load Model

In this paper, a time-varying electrical load model is used to represent different load demands. Load demands are unknown and change as the load power requirements. The average model is

$$\begin{array}{l} \frac{d}{dt}i_L(t) = \frac{1}{L_L}(V_{DC} - i_L R_L) \\ \eta_1 P_{FC} + \eta_2^k P_B = P_L \\ k = \begin{cases} +1 & i_B \geqslant 0 \\ -1 & i_B < 0 \end{cases} \end{array} \tag{4}$$

where η_1 and η_2 are energy conversion efficiency of two DC Converters, V_{DC} is the DC bus voltage, and L_L is the inductance of load. A small inductance L_L is corresponding to small load dynamical change. The value of L_L is unknown and positive, and is assumed to be a constant.

III. Control Development

In this section, the proposed control strategy is given in detail. The objectives of optimization are as follows.

1) Fuel consumption is minimal.
2) The battery SOC is maintained around a given value.
3) The maximum output power of a fuel cell is not infinite.

A. Objective of Optimization

The objective of optimization in this paper is to minimize the hydrogen consumption. In order to In order to reduce the consumption of fuel, it is natural to use hydrogen consumption as an optimization objective. Then, the performance criteria of the optimization problem can be defined as:

$$minimize \quad J(\dot{m}_{H_2}) = \int_{t_0}^{t_f} \dot{m}_{H_2} dt \tag{5}$$

State equations and boundary constraints are described as:

$$\begin{array}{l} \frac{d}{dt}V_s(t) = \frac{1}{C_s}(i_B(t) - \frac{V_s(t)}{R_s}) \\ \frac{d}{dt}V_f(t) = \frac{1}{C_f}(i_B(t) - \frac{V_f(t)}{R_f}) \\ \frac{d}{dt}V_{soc}(t) = \frac{1}{C_b}(-i_B(t) - \frac{V_{SOC}(t)}{R_{sd}}) \\ \frac{d}{dt}i_L(t) = \frac{1}{L_L}(V_{DC}(t) - i_L(t)R_L) \\ V_B(t) = V_{OC}(t) - i_B(t)R_0 - V_s(t) - V_f(t) \\ V_{OC}(t) = aV_{SOC}(t) + b \\ \eta_1 P_{FC} + \eta_2^k P_B = P_L \\ 0 \leq P_{FC} \leq P_{FCmax} \\ SOC_{min} \leq V_{SOC}(t) \leq SOC_{max} \\ V_{SOC}(t_0) = V_{SOC}(t_f) \end{array} \tag{6}$$

Since the mass flow of hydrogen as a reactant is proportional to the fuel cell current, it can be derived as $\dot{m}_{H_2} = \frac{n_{cell} M_{H_2} i_{FC}}{2F}$, where n_{cell} is the number of fuel cells, M_{H_2} is the molar mass of hydrogen, and F is the Faraday constant. Based on (2), (5) can be rewritten as:

$$J(\dot{m}_{H_2}) = \frac{n_{cell} M_{H_2}}{2F} \int_{t_0}^{t_f} \frac{V_0 - \sqrt{V_0^2 - 4R_{FC}P_{FC}}}{2R_{FC}} dt \tag{7}$$

due to $\frac{\partial(\frac{V_0 - \sqrt{V_0^2 - 4R_{FC}P_{FC}}}{2R_{FC}})}{\partial P_{FC}} = \frac{P_{FC}}{\sqrt{V_0^2 - 4R_{FC}P_{FC}}} > 0$, therefore $J(\dot{m}_{H_2})$ is a positive monotonely increasing function of P_{FC}. Therefore minimizing $J(\dot{m}_{H_2})$ is equivalent to minimize the power of FC. The problem is equivalent to minimize the functional of J' in this paper.

$$minimize \quad J'(i_B) = \int_{t_0}^{t_f} \frac{1}{\eta_1}(P_L - \eta_2^k i_B V_B)^2 dt \tag{8}$$

Moreover, a penalty function is introduced to deal with the inequality constraints in (6). The boundary constraints defined in (6) are rewritten as follows:

$$\begin{array}{l} f_1 = P_{FC} = \frac{1}{\eta_1}(P_L - \eta_2^k i_B V_B) \geqslant 0 \\ f_2 = P_{FCmax} - \frac{1}{\eta_1}(P_L - \eta_2^k i_B V_B) \geqslant 0 \\ f_3 = V_{SOC} - SOC_{min} \geqslant 0 \\ f_4 = SOC_{max} - V_{SOC} \geqslant 0 \end{array} \tag{9}$$

In order to ensure the inequality in (9), a penalty function $G(x)$ is defined as $G(x) = e^{-\alpha x}, \alpha > 0$, to analyze the penalty function method further, a cost function is defined in (10).

$$minimize \quad J'' = J' - \int_{t_0}^{t_f} \Sigma_{i=1}^4 \sigma_i G_i f_i^2 dt \tag{10}$$

where $G_i = G(fi)$ is the penalty function defined above, and σ_i are positive penalty factors. Based on the *Lemma* in the Appendix, it can be proved that when σ_i is large enough, J'' and J' are equivalent. Pontryagin's maximum principle [21] is used to solve the variational problem in the following. Based on Pontryagin's maximum principle, the Hamilton function can be constructed as follows, then the necessary condition for optimal i_B can be obtained.

$$\begin{array}{l} H = \frac{1}{\eta_1^2}(P_L - \eta_2^k i_B V_B)^2 - \Sigma_{i=1}^4 \sigma_i G_{f_i} f_i^2 \\ \quad + \lambda_1(t)\frac{1}{C_s}(i_B - \frac{V_s}{R_s}) \\ \quad + \lambda_2(t)\frac{1}{C_f}(i_B - \frac{V_f}{R_f}) \\ \quad + \lambda_3(t)\frac{1}{C_b}(-i_B - \frac{V_{soc}}{R_{sd}}) \end{array} \tag{11}$$

where $\lambda_1(t)$, $\lambda_2(t)$ and $\lambda_3(t)$ are lagrange multipliers. According to the Pontryagin's maximum principle, we can derive the following canonical equations and extreme conditions.

$$\begin{array}{ll} \frac{\partial H}{\partial \lambda_1} = \dot{V}_s & \frac{\partial H}{\partial \lambda_2} = \dot{V}_f \\ \frac{\partial H}{\partial \lambda_3} = \dot{V}_{SOC} & \frac{\partial H}{\partial V_s} = -\dot{\lambda}_1 \\ \frac{\partial H}{\partial V_f} = -\dot{\lambda}_2 & \frac{\partial H}{\partial V_{SOC}} = -\dot{\lambda}_3 \\ \frac{\partial H}{\partial i_B} = 0 & \end{array} \tag{12}$$

Based on the last equation of (12), i_B can be solved as:

$$i_B^* = \frac{1}{2R_0}[V_{oc} - V_s - V_f - \frac{\eta_1(\frac{\lambda_1}{C_s} + \frac{\lambda_2}{C_f} - \frac{\lambda_3}{C_b})}{\eta_2^k(1 - \sigma_1 G_1 + \sigma_2 G_2)}] \tag{13}$$

B. Solving the optimization problem in real-time

The lagrange multipliers defined in (11) play an important role in calculating the derivative of V_s, V_f and V_{SOC}. Besides, based on [19], the capacity of capacitor C_s and C_f are larger than $10^5 F$. Therefore the voltage across the capacitor is relatively stable. The range of variation of the SOC is also small, then we can assume that the change of SOC is negligible. Therefore (14) can be obtained that:

$$\begin{cases} -\dot{\lambda}_1 = \frac{\partial H}{\partial V_s} = 0 \\ -\dot{\lambda}_2 = \frac{\partial H}{\partial V_f} = 0 \\ -\dot{\lambda}_3 = \frac{\partial H}{\partial V_{SOC}} = 0 \end{cases} \Rightarrow \quad \lambda_i^* = constant \tag{14}$$

The lagrange multipliers λ_i need to balance the change of V_s, V_f and V_{SOC}. This means that there is an optimal value for the constant lagrange multipliers for every cycle. According to the method in [22], a state feedback controller is proposed to approach the optimum:

$$\hat{\lambda}_i(t) = \lambda_i^* + K_{P_i} e_i(t) + K_{I_i} \int_0^t e_i(t)dt \quad i = 1,2,3 \tag{15}$$

where λ_i^* is the initial lagrange multipliers, $e_1 \triangleq V_{SOC}^* - V_{SOC}$, $e_2 \triangleq V_s^* - V_s$, $e_3 \triangleq V_f^* - V_f$, and K_{P_i} and K_{I_i} are the proportional and integral constant, respectively, see Fig. 4.

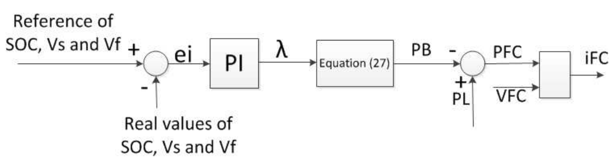

Fig. 4: feedback control

C. Fuzzy Logic Control

As for controller above, the value of i_B has a vital influence on the control performance. i_B fluctuates near the optimal value with the change of the load current and the FC current, the control performance can be improved naturally [23]. It has been proved that fuzzy control is very effective for power distributing in a hybrid power system based on the experimental knowledge [24], [25], [26], [27]. Therefore, fuzzy logic control (FLC) is developed to improve the system performance under different load power. The topology of the fuzzy logic closed-loop system is shown in Fig. 5.

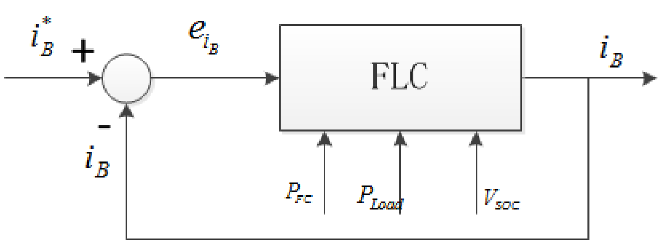

Fig. 5: The topology of the fuzzy logic closed-loop system

The input variables to the FLC are: 1) the error between the P_{load} and P_{FC}; 2) the SOC of the battery. The output variable is i_B. The membership functions for error are negative large (NL), negative middle (NM), negative small (NS), zero (ZO), positive small (PS), positive middle (PM) and positive large (PL), which represent the deviation degree between the power of FC and the power of load. Similarly, the membership functions for SOC are very small (VS), small (S), middle (M), large (L) and very large (VL). As for the membership functions of i_{Bref}, NVL represents negative very large, PVL represents positive very large, and others are same with the membership functions of error. Rules of the FLC under different load power are shown in Table I.

TABLE I: Rule Base on FLC

i_{batref}		error						
		NL	NM	NS	ZO	PS	PM	PL
SOC	VS	NVL	NL	NM	NM	NM	NM	NM
	S	NL	NM	NS	NS	NS	NS	NS
	M	NM	NS	NS	NS	ZO	PS	PS
	L	ZO	ZO	ZO	ZO	PS	PM	PL
	VL	ZO	ZO	ZO	ZO	PS	PM	PVL

IV. Simulation Results

To evaluate the effectiveness of proposed FLC strategy, simulations are carried out. The data of load current changes is from [28]. Since the car starts and stops many times, the load demand changes quickly as shown in Fig. 6. Based on Fig. 7, when the load power increases rapidly, battery can add the required power timely, while the fuel cell increases slowly. The impact of rapid changes of load demand is mainly borne by the battery. Fig. 8 shows the change of battery's current and voltage. The battery current as an auxiliary power source, fluctuates around zero slightly. The load demand become very large after 1000s, and the lithium-ion battery supplies power to the load continuely. At last, the load demand goes back to 0, SOC decreases gradually with the time going on, thus SOC is at a low level. Fig. 8 and Fig. 9 represent that the fuel cell will give more power to charge the battery, so current of battery is negative in Fig. 8. The current of fuel cell has little change in the process in Fig. 10. In the simulation, the derivative of the current is shown. The derivative of the current is less than $5A/s$, for such a change in current has less damage to the fuel cell. Besides, the simulation results of PID control are shown in Fig. 11. After optimization of the current of battery, the current of fuel cell is smoother than non-optimization. Fig. 12 shows the energy consumption results. It is obvious that the energy consumption decreases after optimizing current of battery, which shows the effectiveness of the energy management.

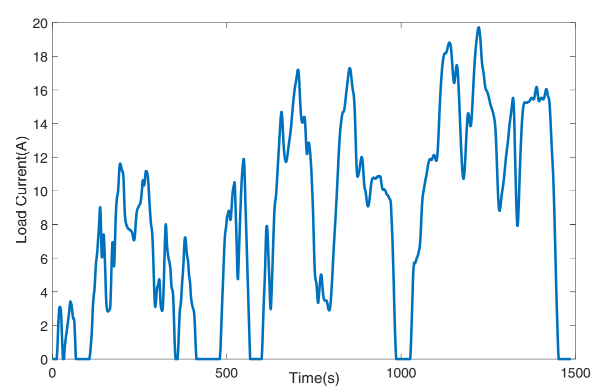

Fig. 6: Load current

V. CONCLUSION

In this paper, an energy management strategy is proposed for hybrid energy system. Then Pontryagin's maximum principle is used to obtain the necessary conditions for optimal i_B.

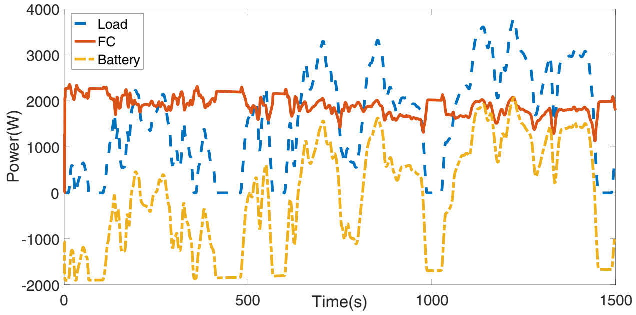

Fig. 7: FC, battery and load power

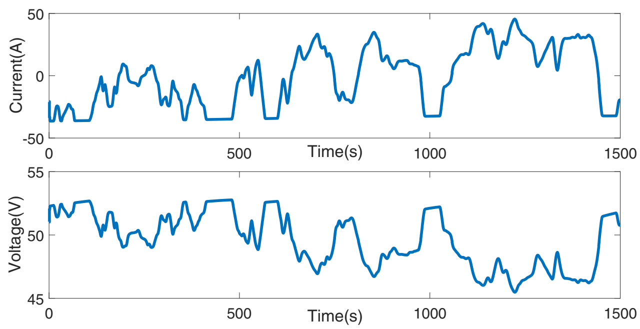

Fig. 8: Battery current and voltage

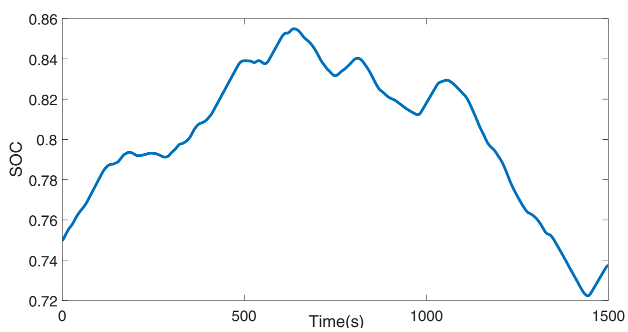

Fig. 9: Battery V_{SOC}

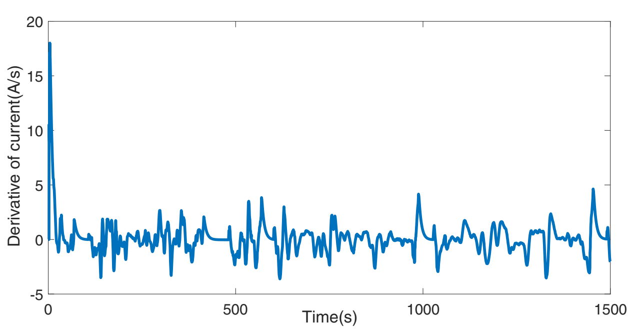

Fig. 10: FC current 's derivative

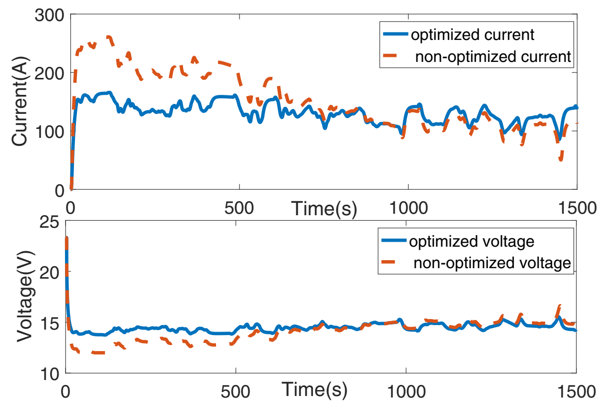

Fig. 11: FC voltage and current

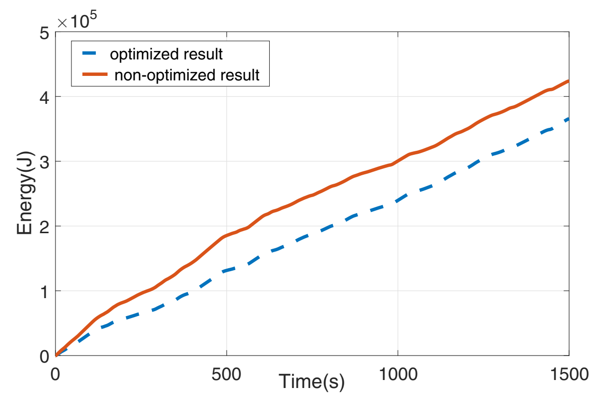

Fig. 12: Energy Consumption

The power of the fuel cell and the SOC of lithium-ion battery pack are taken into consideration as two boundary conditions of energy management. A penalty function is used to ensure the establishment of the two boundary conditions. Besides, real-time optimizing based PI regulation of lagrange multipliers is implemented. For different working conditions, the battery current is given based on the Pontryagin's maximum principle. Real values of the battery current can keep up with reference values of the battery current due to the fuzzy logic algorithm. The simulation results shows that the effect of the mutation of load demand is borne by the battery, the current of fuel cell changes slowly. SOC fluctuates within a certain range. which shows the effectiveness of the proposed energy management method.

APPENDIX

As for a constrained nonlinear optimization problems of the standard form

$$\begin{aligned} &minimize \quad f(x) \\ &\ \ x \in R^n \\ &s.t. \qquad g_i(x) \geqslant 0 (i \in I) \end{aligned} \tag{16}$$

we assume that two conditions are established in the following: (1) Let $f(x)$ and g_i be C^1 functions for all $i \in I$. (2) Let us furthermore assume that the set of gradients $\{\bigtriangledown g_i : i \in I\}$ is linearly independent.

$$\begin{array}{ll} \underset{x \in R^n}{minimize} & f(x)+\sigma_i^T G_i g_i(x) \end{array} \tag{17}$$

Lemma: If x^* is the optimal point of (17), when σ_i approaches infinity, x^* is the optimal point of (16).

Proof: Let x^* be an optimal accumulation point of the sequence of iterates x_k generated by algorithm in (17), and $\lim_{k\to\infty} x_k = x^*$, where $x_k \leqslant x^* \leqslant x_{k+1}$.

$$\begin{aligned} &||f(x_{k+1})+\sigma_i^T(k+1)G_i g_i(x_{k+1})- \\ &f(x_k)-\sigma_i^T(k)G_i g_i(x_k)|| \leqslant \varepsilon \end{aligned} \tag{18}$$

$$||\bigtriangledown f(x_\theta)+\sigma_i^T(\theta)G_i \bigtriangledown g_i(x_\theta)|| \leqslant \varepsilon \tag{19}$$

The triangular inequality is used in conjunction with (19) , we find $||\sigma_i^T(\theta)G_i \bigtriangledown g_i(x_\theta)|| \leqslant \varepsilon + ||\bigtriangledown f(x_\theta)||$, $\sigma_i(\theta)$ is the penalty factors, thus $\sigma_i(\theta) > 0$, it can be obtained that $||G_i \bigtriangledown g_i(x_\theta)|| \leqslant \frac{\varepsilon+||\bigtriangledown f(x_\theta)||}{||\sigma_i(\theta)||}$. Taking the limit at both sides of inequality, we have

$$\lim_{\sigma_i\to\infty} ||G_i \bigtriangledown g_i(x_\theta)|| \leqslant \lim_{\sigma_i\to\infty} \frac{\varepsilon+||\bigtriangledown f(x_\theta)||}{||\sigma_i(\theta)||} = 0 \tag{20}$$

Therefore, the left-hand side of (20) converges to zero, and $\sum_{i\in I} G_i \bigtriangledown g_i(x^*) = 0$. Since $\{\bigtriangledown g_i : i \in I\}$ is linearly independent, it must be true that $G_i = 0 \quad (i \in I)$, which shows that x^* is also the optimal solution of (16).

■

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