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ROBUST ENERGY MANAGEMENT STRATEGY OF FUEL CELL/ULTRACAPACITOR HYBRID-POWERED VEHICLE BASED ON MIN-MAX GAME THEORY

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ABSTRACT

The energy management strategy (EMS) plays an important role in the power system of hybrid-powered fuel cell vehicles in order to reduce hydrogen consumption and fuel cell performance degradation. This paper proposes a robust EMS based on the min-max game theory, where the EMS and the driver behavior are set as two virtual game players making decisions for opposite goals. First, a mathematical model of the hybrid-powered fuel cell vehicle is introduced, that include a transmission system, an ultracapacitor system, a fuel cell system, and the DC/DC converter. Then, a min-max game framework is constructed to describe the energy management problem of fuel cell/ultracapacitor hybrid-powered vehicle with uncertain environment. Finally, the high efficiency and robustness of the proposed strategy are validated by comparing it to the PID-based strategy in the dynamic driving condition.

Keywords: Energy management strategy, Ultracapacitor, PEM fuel cell, Game theory

NONMENCLATURE

Abbreviations	
EMS	Energy management strategy
SR-UKF	Unscented Kalman filter
PMP	Pontryagin's minimum principle
SOC	State of charge
UDDS	Urban Dynamometer Driving Schedule

1. INTRODUCTION

With the depletion of non-renewable energy and air pollution caused by traditional fuel vehicles, the fuel cell vehicles have attracted much attention because of its low pollution, and long mileage. However pure fuel cell vehicles also have some disadvantages, such as slow power response, unable to save energy from braking and low efficiency under small current. Therefore, the fuel cell generally forms the power system of automobiles with energy storage devices (such as ultracapacitor) using to share peak power and make the fuel cell operate at the high efficiency point more stable. The ultracapacitors have higher power density, longer lifetime, better dynamic response and more excellent capability to track the peak power when the required power changes dramatically.

Considering the characteristics of fuel cells and ultracapacitors, the power system performance highly depends on how the output power from the fuel cell and ultracapacitor packs is allocated [1]. A rule-based power distribution strategy with remaining capacity and power capability estimation is proposed in Ref. [2]. Hu et al. [3] discussed the optimal control of an electric bus by using efficient convex programming. Different power system topologies were analyzed in the presented framework. Ettihir et al. [3] addressed the energy management strategy by identifying the model parameters using the square root unscented Kalman filter (SR-UKF) method to find the best operating points. This method can be used to compare the rule-based energy management strategy (EMS) and the optimal EMS based on Pontryagin's minimum principle (PMP). Li et al. [5] developed a fuzzy logic control to design EMS for hybrid vehicles, which can improve the fuel economy and the mileage of the journey. It has been demonstrated in Ref. [6-8] that the game theory can be applied to optimize the power dispatch and hybrid power system planning.

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The organization of this paper is as follows: Section 2 introduces modeling of hybrid-powered fuel cell vehicles including a transmission system, an ultracapacitor system, a fuel cell system, and the DC/DC converter. In Section 3, a robust EMS is proposed based on min-max game theory. In Section 4, the results are compared with the PID-based strategy in a dynamic driving condition to verify the robustness and efficiency. Finally, the conclusions are provided in Section 5.

2. MATHEMATIC MODELING OF HYBRID-POWERED FUEL CELL VEHICLE

The semi-active fuel cell/ultracapacitor hybrid energy system topology is applied in our study. The fuel cell provides the main output power controlled by the DC/DC converter, and ultracapacitor provides peak power that controlled passively. The mathematic modeling of the hybrid-powered fuel cell vehicle is composed of a transmission system, an ultracapacitor system, a fuel cell system, and the DC/DC converter.

2.1 Transmission and vehicle modeling

The motor power Pm can be calculated by the following equations:

$$P_m = \frac{1}{\eta_m}(\mu Mgsin\theta + Mgsin\theta + 0.5\rho_{air}AC_{air}u^2 + \frac{du}{dt}\delta M)v \qquad (1)$$

Where *v* denotes the vehicle speed, *M* denotes the vehicle mass, *μ* denotes the rolling resistance coefficient, ρ_{air} is air density, *g* denotes the gravitational acceleration, *ϑ* denotes the grade of the road, Car denotes the coefficient of air resistance, *A* denotes the windward area of the vehicle, *δ* denotes the correction coefficient of the rotation mass and η_m denotes the efficiency of the transmission system. Parameters values refer to Table 1.

2.2 Ultracapacitor and PEM fuel cell modeling

The standard RC model is used to describe the electrical characteristic of ultracapacitor. The structure of RC model consists of an equivalent resistance Rc and an equivalent capacitance Cm as shown in Fig. 1(a), the terminal voltage Ut and the state of charge (SOC) can be calculated as follows:

$$U_t = U_m - i_c R_c \qquad (2)$$

$$\dot{U}_m = -\frac{i_c}{C_m} \qquad (3)$$

$$SOC(t) = SOC(t_0) - \int_{t_0}^{t} \frac{i_c(t)}{C_m} dt \qquad (4)$$

Where U_m represents the voltage of the equivalent capacitance, i_c represents the current of the ultracapacitor.

In order to describe fuel cell, we model the output characteristic of fuel cell using a polynomial fitting method.

$$P_{fc} = \sum_{i=0}^{2} a_k (i_{fc})^k \qquad (5)$$

Where P_{fc} represents the output power of the fuel cell, i_{fc} represents the current of the fuel cell, a_k is fitting coefficients obtained by least square method using the experimental data shown in Fig. 1. Parameters values refer to Table 1.

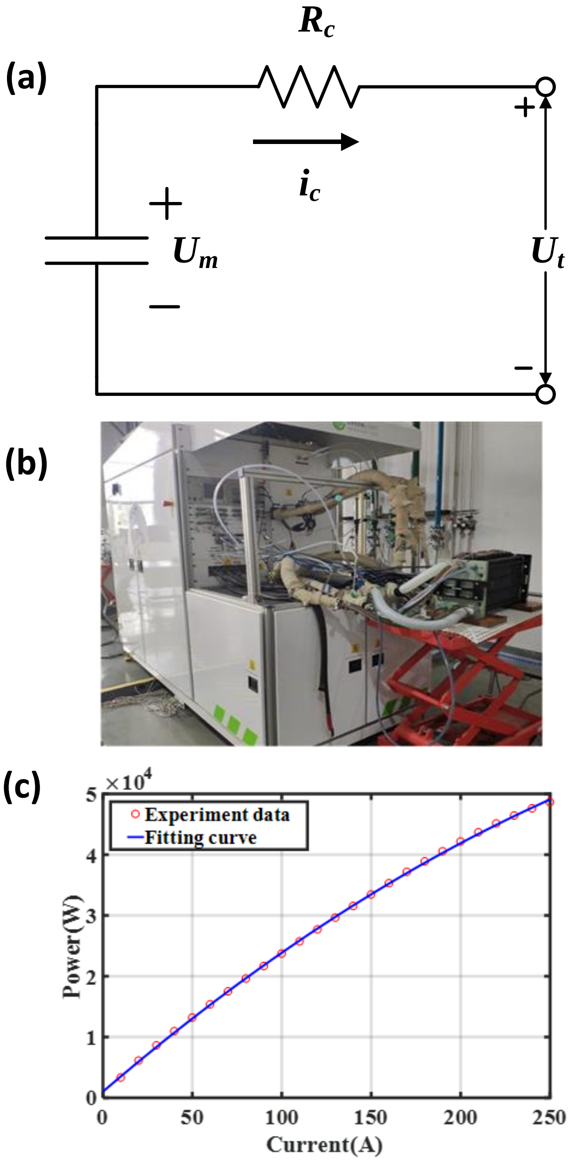

Fig 1. (a) Schematic of ultracapacitor (b) Fuel cell stack test system (c) Test data and fitting curve

Table 1. Parameters of the model

Parameters of the vehicle	Values
Vehicle mass	2800 kg
Density of air	1.202 kg/m^3
Coefficient of air resistance	0.3
Windward area of the vehicle	2 m^2
Rolling resistance coefficient	0.015
Radius of wheels	0.298 m
Efficiency of the transmission system	0.9
Correction coefficient of the rotation mass	1.04
Equivalent resistance	0.0031 Ω
Equivalent capacitance	2.9743×103 F
Fitting coefficients	(-0.23,251.55,1065.7)

2.3 DC/DC converter modeling

In this study, we use an efficient map to describe the operational behavior of the DC/DC converter. As shown in Table 2, the efficiency can be decided by current i_{DC} and power P_{DC}.

Table 2. Efficiency map of the DC/DC converter

$\xi(i_{DC},P_{DC})$	0	5kW	10kW	20kW	30kW
5A	63%	67%	71%	73%	74%
10A	75%	84%	92%	95%	97%
50A	73%	82%	91%	93%	96%
100A	72%	80%	88%	91%	95%
150A	70%	76%	82%	89%	92%

3. ENERGY MANAGEMENT STRATEGY BASED ON MIN-MAX GAME

In this section, a game model is proposed for hybrid vehicle energy management with uncertain environments. EMS and the driver behavior (such as external required power) are set as two virtual game players, which make decisions for opposite goals. The EMS aims to reduce the energy consumption of the power system, keep the SOC of ultracapacitor at the set value, and make the fuel cell system work at the high-efficiency point. On the other hand, driver behavior makes decisions to deteriorate the state of the system. Note that the environment may not change as shown in the min-max game which is set to ensure the robustness of the system.

$$\min_{u\in U}\max_{w\in W} J(u,x,w)=\sum_{t=1}^{N}(\eta u_t^{\,2}+\gamma(z_t-z^*)^2) \qquad (6)$$
$$s.t.\ G(u,x,w)\le 0,\ x\in X$$

Where *u* is the input variable of the power system, which is controlled by energy management. *w* is the external required power that is determined by environments. *x* is the system state variable. *X* is the set of system state. *U* and *W* are strategy sets of energy management and driver behavior.

Associated with the benefit of the robustness of the system which can handle the worst case in the strategy set of environments, the conservative decisions made in the proposed min-max game challenge the efficiency of the energy management system, therefore the strategy set of environments should be determined in an appropriate range.

$$W=\left\{ w_t \left| \begin{array}{l} w_l \le w_t \le w_u \quad (a) \\ \sum_{t=1}^{N}\dfrac{w_t-\hat{w}}{w_h} \le \Gamma \ (b) \end{array} \right. \right\} \qquad (7)$$

$$w_u=\hat{w}+w_h \qquad (8)$$

$$w_u=\hat{w}-w_h \qquad (9)$$

$$w_h=\Phi^{-1}(\frac{1+\alpha}{2})\sigma_w \qquad (10)$$

$$\Gamma=N\mu_w+\Phi^{-1}(\beta)\sqrt{N}\sigma_s \qquad (11)$$

Where w_u and w_l are upper bound and lower bound of *w*. and α and β are the confidence probability of Eq. (7a) and Eq. (7b). σ_w is the variance of $w-\hat{w}$ and σ_s is the variance of $(w-\hat{w})/w_h$, which can be obtained by statistical method. Constraint (7b) restricts the total error over the optimization horizon. Γ is the measure of uncertainty, which is referred to the size of the strategy set of environments. If Γ= 0, the min-max game problem (6) will be a deterministic optimization problem. Considering the real-time capability, we adopt a Markov Chain method with forgetting factor to obtain $\hat{w}$. *w* is divided into N intervals (w_i, i=1, 2, 3… N), the transition probability matrix is given in Eq. (12).

$$p_{i,j}=\frac{\frac{1}{L}\sum_{t=1}^{L}f_{i,j}(t)}{\frac{1}{L}\sum_{t=1}^{L}f_i(t)}=\frac{(1-\mu)F_{i,j}(L-1)+\frac{1}{L}f_{i,j}(t)}{(1-\mu)F_i(L-1)+\frac{1}{L}f_i(t)} \qquad (12)$$

$$F_{i,j}(L)=\frac{1}{L}\sum_{t=1}^{L}f_{i,j}(t) \qquad (13)$$

$$F_i(L)=\frac{1}{L}\sum_{t=1}^{L}f_i(t) \qquad (14)$$

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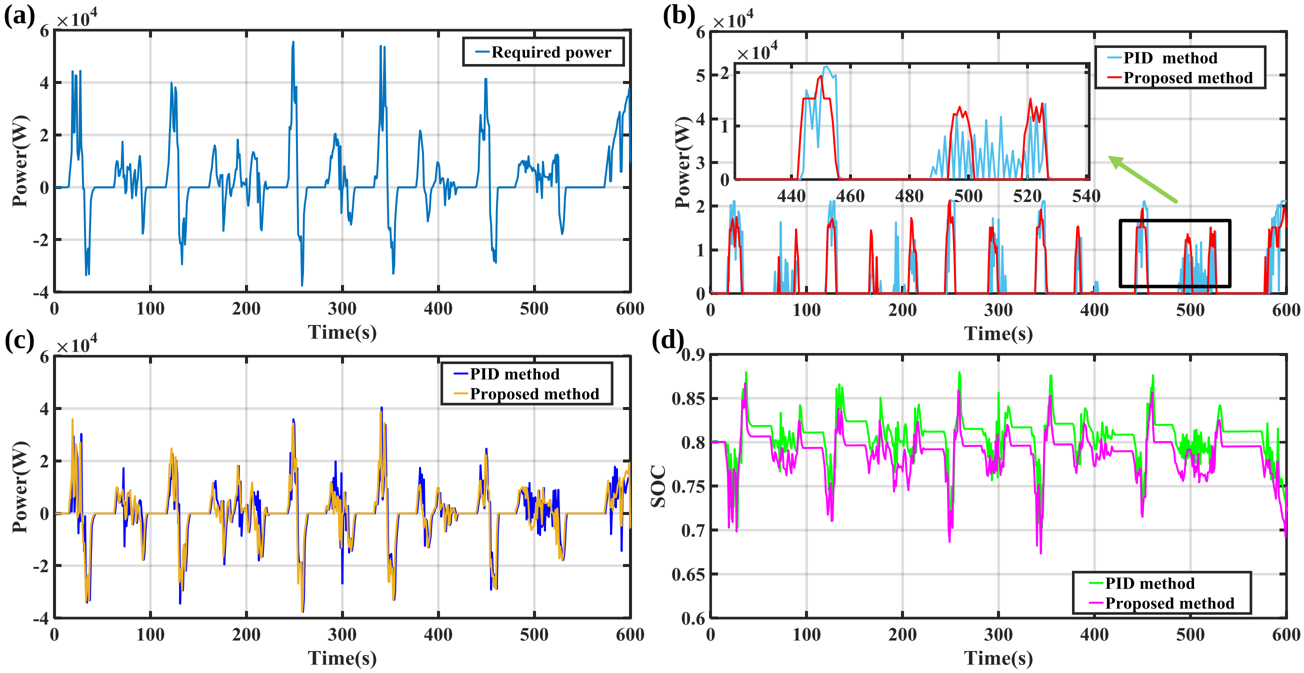

Fig 2. Comparison results of simulation. (a) Required power of dynamic driving cycle (b) Power of fuel cell (c) Power of ultracapacitors (d) SOC of ultracapacitors

$$\hat{w}_{k+1}=\sum_{j=1}^{N}p_{ij}\hat{w}^{j}(\hat{w}_{k}\in\hat{w}^{i}) \tag{15}$$

Where $f_{i,j}(t)$ is the transition event from w^{i} to w^{j} . $F_{i,j}(L)$ is the frequency of $f_{i,j}(t)$ during time L. μ is called the forgetting factor introduced to the effective memory depth, which is chosen from 0 to 1.

An iterative algorithm using the relaxation procedure for the min-max problem is represented as follows [9]:

Step1: Initialize the $w^{1}\in W$. Set i = 1. Obtain W from Eq. (7) by calculating Eq. (7-15).

Step2: The current relaxed problem with the constraints by the introduction of new variables σ and λ is shown in Eq. (16). An optimal solution (u^i, σ^i, λ^i, x^i) is obtained by solving the minimization problem (16).

Step3: By solving the maximization problem (17), we can get the optimal wi which is chosen from strategy sets of environments. The maximal value $h(u^{i},\lambda^{i},x^{i},w^{i})=J-\lambda G$.

Step4: If $h\le\sigma^{i}+\varepsilon$, terminate, where ε is a constant. u^{i} is a solution for the min-max problem (6). If $h>\sigma^{i}+\varepsilon$, i=i+1, add $J(u,x,w^{i})-\lambda G(u,x,w^{i})\le\sigma$ as a new constraint to the problem (16) and go back to step2.

$$\begin{gathered}\min_{(u\in U,x\in X,\lambda>0,\sigma)}\sigma\\ \text{s.t. } J(u,x,w^{i})-\lambda G(u,x,w^{i})\le\sigma\ (i=1,2,3...)\end{gathered} \tag{16}$$

$$\max_{w\in W}J(u^{i},x^{i},w)-\lambda^{i}G(u^{i},x^{i},w) \tag{17}$$

4. VERIFICATION AND DISCUSSION

To verify the efficiency and robustness of the proposed method, the simulations are implemented on a driving condition mixed the Manhattan driving cycle and EUDC driving cycle as shown in Fig. 2(a). The comparison results of the proposed robust energy management strategy and the PID method are displayed in Fig. 2(b) (c) and (d).

The comparison of the power of fuel cell indicates that the proposed strategy can reduce the power fluctuation of fuel cell and makes the fuel cell operating point more stable than the PID method. Because the proposed strategy based on the min-max game theory takes into account the worst possible condition in the future, the SOC of ultracapacitors is kept closer to the set point under drastic changes in required power than the PID method. The hydrogen consumptions are 0.0258 kg in the proposed strategy and 0.0277 kg in the PID method that means the proposed power management strategy can improve the system efficiency.

Table 2. Simulation results of different strategies.

Parameters of the vehicle	Proposed method	PID method
Hydrogen consumption (kg)	0.0258	0.0277
The standard deviation of power of fuel cell (kW)	3.9	7.1
Number of start and stop	16	54

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5. CONCLUSIONS

In this paper, a robust energy management strategy of fuel cell/ultracapacitor hybrid-powered vehicle is proposed based on the min-max game theory considering the uncertain environments. The EMS and driver behavior are set as two virtual game players. The strategy sets of environments are obtained by a Markov Chain and statistical method, and the min-max game problem is solved by an iterative algorithm using the relaxation procedure. On one hand, this strategy can make the fuel cell work with less power fluctuation, which can prolong the lifetime of the fuel cell. On the other hand, the fuel cell can operate near the highest efficiency point more stable under changing the environment, therefore the hydrogen consumption of the power system with the proposed strategy is less than that using the PID-based strategy.

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