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ABSTRACT The energy management strategy is the key to achieve fuel cell hybrid system operation with high-efficiency and low-energy cost. The widely used energy management strategies are established based on the fixed models of power sources energy consumption and efficiency. However, due to the gradual performance degradation of the fuel cell during the service period, some model parameters will change significantly and the fixed models will become increasingly inaccurate over time. Therefore, this paper established time-varying models of power sources energy consumption and efficiency by introducing the fuel cell degradation rate. On this basis, in order to reduce the energy consumption of the system, improve the fuel cell efficiency and relatively maintain the SOC level, a novel dual-mode energy management strategy, DMDEE, for hybrid vehicles is proposed. In order to improve the online operation speed of proposed energy management strategy, the optimal control rules are obtained by offline calculation first. Then through comparison experiments with other two energy management strategies, PMP and PF, it is verified that the proposed strategy can effectively reduce the system energy consumption and improve the efficiency of the fuel cell system, meanwhile can make the SOC regress after it deviates from its ideal working area. In addition, the mode switching hysteresis control is also validated. Therefore, the effectiveness and superiority of the proposed energy management strategy in this paper has been verified.

INDEX TERMS Fuel Cell Vehicle; Energy Management Strategy; Fuel Cell Degradation; Energy Consumption; Fuel Cell Efficiency

I. INTRODUCTION Nowadays, the hydrogen energy is undergoing dramatic development, and will be the ultimate energy source of human beings in future. Moreover, the fuel cell is one of the most widely used ways of hydrogen energy and has caused great attention and research all over the world. Fuel cell has the advantage of high efficiency, energy density and no pollution, which leads to its wide application in transportation, aircraft and distributed generation [1-5]. Specifically, in the field of electric vehicle, the fuel cell vehicle has showed its tremendous advantages and development potentials when composing a hybrid system with energy storage systems [6-10].

The research of fuel cell hybrid vehicle concentrates on its hybrid system modeling, parameter matching strategies and energy management strategies, and what this paper mainly focus is the last one. The energy management strategy distributes required power between fuel cells and the others power sources, and it can help to improve system efficiency and reduce hydrogen consumptions to utilize an optimized one, which means a lot to fuel cell hybrid system [11-16].
At present, the common-used energy management strategies for fuel cell hybrid systems can be divided into two types, rules-based and optimization-based respectively [17-19]. The rule-based control strategy is easy to implement and practical. Its control logic is mainly dependent on the understanding of the working characteristics of various components of the hybrid system and related engineering experience, including: state machine strategy [20-21], wavelet-fuzzy logic strategy [22-23], power following strategy [24-25], but the control effect is relatively poor. The energy management strategy based on optimization can be divided into global optimization and instantaneous optimization energy management strategies [18]. They have the characteristics of good optimized effect and large calculation amount. The dynamic programming (DP) [26-27], Pontryagin minimum principle (PMP) [28] and equivalent hydrogen consumption minimum strategy (ECMS) [29-30] all can be classified to this type. In the Ref [28], Liangfei Xu sets the control strategy of the fuel cell start-stop, normal operation mode and fault state by applying the PMP control strategy to optimize the fuel economy of fuel cell vehicles; In the Ref [29], García P et al. applied the equivalent hydrogen consumption minimum algorithm to the fuel cell/battery/supercapacitor hybrid system and achieved good results; In the Ref [30], Zhihu Hong et al. introduced the dynamic power factor to the ECMS strategy, making it more suitable for the working conditions of the locomotive; In the Ref [31], Guorui Zhang proposed a coupled power-voltage equilibrium strategy based on the droop control for fuel cell/battery/supercapacitor tramway and it was proved the proposed strategy possessed good economic performance and robustness.

In essence, an optimization-based energy management strategy is an optimization problem. However, in various optimization-based energy management strategies, the objective functions do not change with the service time of power sources, and the parameters in the objective function are also experimentally determined based on the initial performance of the power sources. In reality, however, the power source will degrade with service time, causing the internal characteristics of the power sources will change and the parameters in the objective function to be changed as well. For example, if the fixed-parameter fuel cell hydrogen consumption model is used, it will cause the hydrogen consumption calculation to be increasingly inaccurate over service time due to fuel cell degradation. Therefore, if the energy management is established based on the objective function with fixed parameters, there will be a deviation between the calculation result and the actual optimal results. This paper considers and only considers the performance degradation of the fuel cell system with service time, and then establishes the time-varying models of instantaneous hydrogen consumption and efficiency. On this basis, this paper designs an energy consumption and efficiency comprehensive energy management strategy.

Moreover, a lot of energy management strategies pay much attention to the maintenance capability of the battery SOC, for example, the battery SOC is required to remain consistent in the beginning and the end of the working conditions, or fluctuate around the target value, just like PMP and PF strategies respectively. In these ways, it is bound to sacrifice some other performance to ensure the maintenance capability of the battery SOC, for example, when the SOC is low, the fuel cell is usually required to output at a high level, which leads to the hydrogen consumption increasing and fuel cell system efficiency decreasing. But, actually, the purpose of adding the battery as an auxiliary power source is to protect the fuel cell and improve the whole performance of the hybrid system, such as energy consumption, efficiency and dynamic response capability, however, forcing the maintenance capability of the SOC is contrary to this purpose. Therefore, in order to avoid this problem, this paper no longer forces the maintenance capability of the battery SOC, and let that SOC fluctuates freely in its ideal working area, in exchange for improving other overall performance of hybrid power system.

II. Hybrid System Description of Fuel Cell Vehicle

The research that this paper based on has developed a fuel cell hybrid prototype vehicle, which is shown in Fig.1, and its key parameters are shown in Tab.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>1350kg</td>
<td>Top Speed</td>
<td>30 km/h</td>
</tr>
<tr>
<td>Capacity</td>
<td>12 Persons</td>
<td>Max Climbing Angle</td>
<td>30%</td>
</tr>
<tr>
<td>Max Load</td>
<td>800 kg</td>
<td>DC Bus Voltage</td>
<td>64 V</td>
</tr>
<tr>
<td>Size(mm³)</td>
<td>5200 × 1490 × 2080</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Due to the soft output characteristics of the fuel cell, the problem of poor dynamic performance may be caused when it drives the vehicle alone. Therefore, the energy storage equipment is generally added to the vehicle as an auxiliary power source to form a hybrid system together with the fuel cell then to power the vehicle. In this vehicle, an air-cooled PEMFC is utilized to work as the main power source, while the lithium battery is utilized as the auxiliary one. For reducing the control difficulty and improving system stability, this paper utilized a common hybrid system topology as Fig.1 shows where the PEMFC is connected to the DC bus via a unidirectional DC/DC converter that is not only used to match the PEMFC output voltage to the DC bus voltage, but also to control the PEMFC output power indirectly, while the battery connected to DC bus directly. In such a system, the PEMFC supplies electricity when traction, and the battery supplies rapid required power and recycles braking energy to improve energy efficiency. In addition, the vehicle auxiliary system, such as lights, wipers and so on, is power by the
battery through a series of DC/DC converters. Battery state of charge (SOC) is collected by the battery management system (BMS), and the hybrid system controller (HSC) is used to distribute the load power and control the whole hybrid system. Then the fuel cell hybrid system powers the motor through a three-phase inverter. In order to observe the output states of power sources and save the data in the operation, this paper also designed the operation monitoring system based on Labview host computer and data acquisition card, also shown in Fig. 1.

II.1 Proton exchange membrane fuel cell (PEMFC)

In this prototype vehicle, a 3kW air-cooled PEMFC produced by Horizon Company, H-3000, is adopted according to the parameters matching calculation. Its key parameters are shown in Tab.2 and its initial polarization curves are shown in Fig.2.

Tab. 2 Key Parameters of H-3000 PEMFC

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Value</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell Numbers</td>
<td>72</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Rated Power/W</td>
<td>3000</td>
<td>72</td>
<td>0.0</td>
</tr>
<tr>
<td>Operation Temperature/°C</td>
<td>5~30</td>
<td>45~55</td>
<td></td>
</tr>
</tbody>
</table>

![Fig.2 Initial Polarization Curves of H-3000 PEMFC](image)

The air-cooled fuel cell system generally includes a fuel cell stack and an auxiliary system, and the auxiliary system includes a controller, a fan, and a solenoid valve. As a result, the fuel cell system efficiency includes two parts, stack efficiency and the system electrical efficiency, and can be obtained by multiplying them, as:

\[
\begin{align*}
\eta_{fcs} &= \eta_{stack} \times \eta_f \\
\eta_{stack} &= \frac{V_c}{E} \\
E_{fcs} &= P_{fc} / P_{stack} = (P_{fc} - P_{aux}) / P_{fc}
\end{align*}
\]  

![Fig.3 Efficiency Curves of H-3000 PEMFC](image)

II.2 Battery Pack

In this prototype vehicle, a 64V60AH lithium battery pack is adopted according to the parameters matching calculation. Its key parameters are shown in Tab. 3.
Tab. 3 Key Parameters of the 64V60AH lithium battery pack

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serial Number</td>
<td>20</td>
<td>Single Cell Rated</td>
<td>3.2V</td>
</tr>
<tr>
<td>Charge Cutoff Voltage</td>
<td>3.7</td>
<td>Discharge Cutoff</td>
<td>2.5V</td>
</tr>
<tr>
<td>Maximum Charge</td>
<td>60A</td>
<td>Maximum Discharge</td>
<td>240A</td>
</tr>
<tr>
<td>Current</td>
<td>(1C)</td>
<td>Current</td>
<td>(4C)</td>
</tr>
</tbody>
</table>

Due to the output characteristics and efficiency characteristics of the utilized battery pack are important for the hybrid system energy management strategy design, this paper uses NI Labview host computer, DC power supply and electronic load both manufactured by ITECH and so on to form a battery test platform to test the open circuit voltage $U_{ocv}$ and internal resistance of utilized battery pack, including charging internal resistance $R_{chg}$ and discharging internal resistance $R_{dis}$, which are all show as Fig.4.

![Actual data vs. Fitting Curve](image)

And in order to facilitate the energy management design and analysis below, the test data is fitted by polynomial, and the fitting result is:

$$U_{ocv} = 43.7 \cdot \text{SOC}^3 - 66.8 \cdot \text{SOC}^2 + 40.6 \cdot \text{SOC} + 52.8$$

$$R_{dis} = -0.06 \cdot \text{SOC}^3 + 0.13 \cdot \text{SOC}^2 - 0.08 \cdot \text{SOC} + 0.08 \quad (2)$$

$$R_{chg} = -0.05 \cdot \text{SOC}^3 + 0.11 \cdot \text{SOC}^2 - 0.07 \cdot \text{SOC} + 0.08$$

Then according to the battery efficiency calculation formula is:

$$\eta_{dis} = \frac{1 + \sqrt{1 - 4R_{dis}P_{bat}}}{U_{ocv}}$$

$$\eta_{chg} = \frac{2}{1 + \sqrt{1 - 4R_{chg}P_{bat}}U_{ocv}^2}$$

Where $P_{bat}$ is the battery power, and it takes a positive value to represent discharging, while a negative value to represent the charging. Then based on the test above, the battery charging and discharging efficiency can be obtained as Fig.5 shows.

![Battery Charging and Discharging Efficiency](image)


This paper proposed a dual-mode energy management strategy, in which the hybrid system works at optimal performance mode (OPM) or state regression model (SRM) according to the battery SOC state. Firstly, when battery SOC is in its ideal working area (IWA), in order to make the battery play a greater role in the system optimal operation, this paper applies no external control to force the maintenance the battery SOC and lets the SOC fluctuate freely in IWA, meanwhile only optimizes the system energy consumption and fuel cell efficiency. Secondly, however, when at OPM, the battery outputs passively, which may cause the problem of SOC deviation form IWA affected by working conditions. When the problem occurs, the hybrid system is needed to work at SRM to apply control to battery to make SOC regress to IWA, and this paper also designs the optimal SOC regress strategy based on battery power loss and regress time optimized. Furthermore, in order to avoid frequent switching of operating modes, this paper also designs the relevant hysteresis control. The structure of DMDEE is shown in Fig.6.

As Fig.6 shows, $soc_{low}$ and $soc_{high}$ means the lowest and highest limitations of IWA respectively, meanwhile, they also mean the falling and rising edges of SOC increasing and decreasing regressing hysteresis control, while the relevant rising and falling edges are represented by $soc_{hcl}$ and $soc_{hch}$ respectively.
III. Optimal Performance Mode of Hybrid System (OPM)

By introducing the index of fuel cell degradation rate $D\%$, which is mentioned and defined in the Ref [32], the time-varying hybrid system energy consumption model is established, including time-varying fuel cell instantaneous hydrogen consumption model and battery equivalent instantaneous hydrogen consumption model, together with the equivalent consumption theory, then the DMDEE strategy is proposed in this paper. When the fuel cell hybrid system is operating at OPM, the proposed DMDEE strategy is utilized to allocate the load power between the fuel cell system and the battery for optimizing system energy consumption and fuel cell efficiency.

In DMDEE, the fuel cell hydrogen consumption also can be expressed as follows:

$$C_{fc} = n \cdot \frac{P_{fc}}{2V_c F}$$  \hspace{1cm} (4)

Where $C_{fc}$ represents the fuel cell hydrogen consumption rate in mol/s; $n$ represents the number of cells of stack; $P_{fc}$ represents the output power of fuel cell system in kW; $V_{stack}$ represents the voltage of the stack in V; $F$ is Faraday constant, this paper takes 96500C/mol.

Since the molar mass of hydrogen is 2.02 g/mol, the expression of the above formula can be converted into:

$$C_{fc} = n \cdot \frac{2.02P_{fc}}{2V_c F} = n \cdot 1.05 \times 10^{-2} \times \frac{P_{fc}}{V_{stack}}$$  \hspace{1cm} (5)

Where $C_{fc}$ represents the fuel cell hydrogen consumption rate in g/s.

Considering the energy loss caused by the conversion efficiency of fuel cell system, the above formula can be rewritten as:

$$C_{fc} = n \cdot \frac{2.02P_{fc}}{2V_c E_{fcs} \eta_{stack} F} = n \cdot 1.05 \times 10^{-2} \times \frac{P_{fc}}{V_{stack} E_{fcs} \eta_{stack}}$$  \hspace{1cm} (6)

As Ref [32] described, the degradation rate of fuel cell can be expressed as the voltage difference between fuel cell model voltage $V_{model}$ and the measured value $V_{stack}$ as:

$$D\% = \frac{V_{inimodel} - V_{stack}}{c}$$  \hspace{1cm} (7)

Where $D\%$ represents the fuel cell degradation rate, and $c$ represents the maximum difference between $V_{inimodel}$ and $V_{measure}$, which can be calculated as:

$$c = d\% \cdot V_{inimodel}$$  \hspace{1cm} (8)

Where $d\%$ represents the maximum percentage of voltage drop allowed, and once this value is reached, the fuel cell should be considered scrapped. In this paper, $d\%$ takes the value of 0.2.

The $V_{inimodel}$ and $\eta_{stack}$ are functions of $P_{stack}$ and $V_{inimodel}$ respectively, and $E_{fcs}$ is a function of $P_{fc}$, therefore, solving the simultaneous formulas, a time-varying fuel cell hydrogen consumption model can be established based on the fuel cell initial polarization curve as follows:

$$C_{fc}(P_{fc}) = \frac{n \cdot 1.05 \times 10^{-2} \times P_{fc}}{(1 - D\% \cdot d\%)^2 \cdot V_{inimodel}(P_{stack}) \cdot E_{fcs}(P_{fc}) \cdot \eta_{stack}(V_{inimodel})}$$  \hspace{1cm} (9)

According to the experiment data of Horizon H-3000, the relationship between fuel cell hydrogen consumption rate $C_{fc}$ with fuel cell system power $P_{fc}$ and fuel cell degradation rate $D\%$ can be shown as Fig.7.

![Fig.7 Horizon H-3000 PEMFC Hydrogen Consumption Rate](image)

On the other hand, according to the equivalent consumption theory, the instantaneous equivalent hydrogen consumption rate of the battery can be expressed as:
Where $C_{fc,avg}$ and $P_{fc,avg}$ represents the average values of hydrogen consumption rates and powers of fuel cell, and $m$ represents the ratio of them, which is also a function of fuel cell degradation rate. By the calculations above, the changes of $m$ ($g \cdot s^{-1} \cdot kW^{-1}$) with the degradation rate is shown in the Fig.8.

As a result, considering that the energy management problem is an optimization problem, the objective function of the problem is:

$$J_1 = C_{fc} + \xi \cdot C_{bat}$$

$$\xi = (1 - d\% \cdot D\%)$$

Where $J_1$ is the cost function, $\xi$ is a correction factor, related to $d\%$ and $D\%$, and is used to reduce the proportion of fuel cell output power in the hybrid system when the fuel cell degradation occurs to make the fuel cell work at high efficiency areas.

The constraints to be satisfied in the optimization problem solving process include fuel cell output power constraint equation, load power balance constraint equation and fuel cell output power volatility constraint equation, as:

$$P_{fcmin} \leq P_{fc} \leq P_{fcmax}$$

$$P_{fc} + P_{bat} = P_{load}$$

$$|\Delta P_{fc}| \leq P_{scope}$$

Where $P_{scope}$ in kW/s represents the maximum volatility of fuel cell output power.

In order to realize the real-time online energy management of fuel cell hybrid system, the objective function $J$ is optimized offline at first, meanwhile the optimal control rules can be obtained, which actually are the mapping from a three-dimensional input array to a one-dimensional output array. As shown in Fig.11, the three-dimensional input variables include the load power $P_{load}$, the battery SOC and fuel cell degradation rate $D\%$, while the one-dimensional output variable is the optimal fuel cell power $P_{scope}$. Specifically, based on MATLAB, this paper uses the fminbnd function to get the optimal output value,
$P_{\text{fcopt}}$ for every three-dimensional combinations of discretized input variables, then, as shown in Fig.11, saves the results $P_{\text{fcopt}}$ into a three-dimensional array, composed of $n$ tables, where $n$ means that the $D\%$ value range [0,1] is equally divided into $n$ parts.

In this way, this paper obtained the optimal fuel cell power control rules in OPM, as Fig.12 shows.

$$\begin{align*}
P_{\text{load}} & \rightarrow \text{SOC} \rightarrow \text{DMDEE method} \\
P_{\text{fcopt}} & \rightarrow \text{SOC} \rightarrow D\% \end{align*}$$

Fig.11 The Schematic Diagram of Proposed DMDEE Strategy

Fig.12 The Value of $P_{\text{fcopt}}$ With Load Power and SOC Under Different Fuel Cell Degradations

**III. II State Regression Mode of Hybrid System (SRM)**

Since it does not consider to maintain the battery SOC at OPM, so the battery outputs passively. As a result, the battery SOC may exceed the range limits of IWA. In order to make the hybrid system work at OPM as much as possible, it is necessary to make the SOC regress to IWA as soon as possible. In addition, the issue of energy losses is also needed to be optimized in the SOC regression process.

As a result, in this paper, the cost function in SRM is established as:

$$J_2 = C_{\text{loss.bat}} + \rho \cdot C_{\text{time}} \quad (13)$$

Where, when in SOC increasing regression process,

$$\begin{align*}
C_{\text{loss.bat}} &= (I_{\text{bat}} \cdot \eta_{\text{chg}})^2 \cdot R_{\text{int}} \\
C_{\text{time}} &= Q_{\text{bat}} / (I_{\text{bat}} \cdot \eta_{\text{chg}}) \\
\rho &= 0.5 \cdot (SOC - SOC_{\text{max}}) / (SOC_{\text{max}} - SOC_{\text{min}}) \quad (14) \\
I_{\text{bat}} &= (U_{\text{ocv}} - U_{\text{ocv}}^2 - 4P_{\text{bat}} \cdot R_{\text{int}}) / 2R_{\text{int}}
\end{align*}$$

and when in SOC decreasing regression process,

$$C_{\text{loss.bat}} = (I_{\text{bat}} / \eta_{\text{dis}})^2 \cdot R_{\text{int}}$$

$$C_{\text{time}} = Q_{\text{bat}} / (I_{\text{bat}} / \eta_{\text{dis}})$$

$$\rho = 0.5 \cdot (SOC - SOC_{\text{min}}) / (SOC_{\text{max}} - SOC_{\text{min}}) \quad (15)$$

$$I_{\text{bat}} = (U_{\text{ocv}} - U_{\text{ocv}}^2 - 4P_{\text{bat}} \cdot R_{\text{int}}) / 2R_{\text{int}}$$

Where, $C_{\text{loss.bat}}$ represents the battery power losses rate in W/s; $C_{\text{time}}$ represents the battery SOC regression time under such a power in the unit of hour; $\rho$ is the regression time penalty factor, in which $\mu$ is a constant that represents the SOC regression speed that the designer wants, ranging from 0 to 1. And here, since the internal resistance of the battery $R_{\text{bat}}$ hardly changes within a relatively small SOC interval, it is considered to be a constant and takes 60m$\Omega$ and 50m$\Omega$ when charging and discharging respectively. The key parameters of SRM in this paper are shown in Tab.4, while the Hysteresis control of modes is shown in Fig.13 as well.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOC$_{\text{max}}$</td>
<td>0.550</td>
<td>SOC$_{\text{max}}$</td>
<td>0.850</td>
</tr>
<tr>
<td>SOC$_{\text{min}}$</td>
<td>0.450</td>
<td>SOC$_{\text{min}}$</td>
<td>0.750</td>
</tr>
<tr>
<td>Hysteresis Control Rising Edge</td>
<td>0.525</td>
<td>Hysteresis Control Falling Edge</td>
<td>0.775</td>
</tr>
<tr>
<td>Hysteresis Control Falling Edge</td>
<td>0.500</td>
<td>Hysteresis Control Rising Edge</td>
<td>0.800</td>
</tr>
</tbody>
</table>

Tab.4 Key Parameters of SRM

**SOC increasing regression process SOC decreasing regression process**

Fig.13 Hysteresis Control of Modes

Similarly, based on MATLAB, this paper uses the fminbnd function to get the optimal battery power $P_{\text{batopt}}$ under every SOC value with different values of $\mu$ (from 0.1 to 1), as Fig.14 shows, in SOC increasing or decreasing regression process. And this paper takes $\mu$ as 0.5.

Due to it is impossible to control the charging and discharging powers of the battery in such a topology in which the battery is connected to the DC bus directly, in this paper, the fuel cell power $P_f$ is the control variable as well when the hybrid system works at SRM. And the $P_f$ control rules are:

$$P_f = \begin{cases} 
P_{\text{load}} - P_{\text{batopt}}, & P_{f\text{c min}} \leq P_{\text{load}} - P_{\text{batopt}} \leq P_{f\text{c max}} \\
0, & P_{f\text{c min}} \leq P_{\text{load}} - P_{\text{batopt}} \leq P_{f\text{c min}} \\
P_{f\text{c max}}, & P_{l\text{oad}} - P_{\text{batopt}} \geq P_{f\text{c max}}
\end{cases}$$

(16)
IV. Results and Analysis

In order to test the proposed energy management strategy and compare it with other strategies, this paper did comparative experiments based on the prototype vehicle measured working condition, shown in Fig. 15. And the fuel cell degradation rate D% of this paper is obtained by the actual fuel cell voltage under this working condition, and is shown in Fig.16.

In this paper, three energy management strategies are used to conduct comparative experiments, including power following strategy (PF), Pontryagin minimum principles strategies (PMP) and proposed DMDEE strategy. First, when the initial value of the SOC is equal to 0.6, the fuel cell power and the battery power under three energy management strategies are as shown in Fig.17 and Fig.18 respectively. Under the power following strategy, since the initial SOC is less than the target value, the fuel cell not only needs to satisfy the load power but also needs to charge the battery, so the average fuel cell power is the largest and the most unstable; under the DMDEE strategy, since the fuel cell has already degraded, the fuel cell power is artificially reduced, so the average output power of the fuel cell is the minimal; under the PMP strategy, the fuel cell power is the most stable.

The overall hydrogen consumptions of the hybrid system under three strategies are shown in the Fig.19, and are 70g, 48.24g and 48.11g respectively under PF, DMDEE and PMP strategy. Moreover, the PMP strategy is an optimization strategy whose optimization results are similar to dynamic programming (DP), and it is easy to prove that its optimal solution is independent of fuel cell degradation rate by adjusting co-state variable λ. As a result, in the working conditions and fuel cell state in this paper, the energy consumption result of PMP can be approximately regarded as the theoretical optimal result. It can be seen from the Fig.19 and the results, that the whole equivalent hydrogen consumption of the DMDEE strategy is always
very close to the PMP strategy, so DMDEE can be considered to optimize system energy consumption well. Both the PMP and DMDEE have obvious optimization effects compared to PF.

Fig. 20 shows the fuel cell system efficiency curves for the three strategies. The average fuel cell efficiency of the DMDEE strategy is 0.4312, while 0.4205 for PMP, and 0.3867 for PF, which indicating that the DMDEE strategy can improve fuel cell system efficiency as fuel cell degrades compared to PF and PMP.

Fig. 21 shows the battery SOC curves under three strategies, in which SOC varies from 0.6 to 0.5852 under DMDEE, while from 0.6 to 0.6371 for PF and from 0.6 to 0.6 for PMP. Since the co-state variables of PMP strategy is offline-solved first, the SOC can return to its initial state; on the other hand, due to the low initial value of SOC, the SOC is required to keep approaching the target value under PF, which leads to an increase in energy consumption and a decrease in fuel cell efficiency; DMDEE does not consider the SOC maintenance ability, thus causing a decline in SOC, but improves the efficiency of the fuel cell system compared to the PMP strategy.
the SOC has returned to IWA, the system works in OPM and works according to the fuel cell optimal control rules, and its output is relatively stable.

The overall hydrogen consumptions of the hybrid system under three strategies are shown in the Fig.24, and are 56.74g, 50.77g and 48.15g respectively under PF, DMDEE and PMP strategy, here the PMP result also can be approximately regarded as the global optimal solution, which shown that both the PMP and DMDEE have obvious optimization effects compared to PF and the optimization result of PMP is 5.14% better than DMDEE.

Fig.25 shows the fuel cell system efficiency curves for the three strategies. The average fuel cell efficiency of the DMDEE strategy is 0.4400, while 0.4251 for PMP, and 0.4400 for PF, which indicating that the DMDEE strategy can improve fuel cell system efficiency as fuel cell degrades compared to PF and PMP.

Fig.26 shows the battery SOC curves under three strategies, in which SOC varies from 0.8 to 0.7678 under DMDEE, while from 0.8 to 0.7328 for PF and from 0.8 to 0.8040 for PMP. This paper hopes that the battery SOC of the hybrid system can be maintained in the IWA. Therefore, although the energy consumption under the PMP strategy is the lowest, but the SOC continues to increase at a higher level, and the distance to IWA further increases, which is opposite from the desired results. For PF and DMDEE, although the SOC regression speed is lower under DMDEE, but the energy loss and the hybrid system overall equivalent hydrogen consumption is reduced, which is more meaningful for improving system performance. And from Fig.26, the SOC reaches to 0.775 at the 384.6s, and before this moment, the hybrid system works at SRM while at OPM after this moment, moreover, from 415.6s to 436s, the SOC is a litter higher than 0.775, but the system still works at OPM.It proved that the dual-mode operation strategy and hysteresis control of this paper are feasible.
Fig. 26 Battery SOC Curves Under Three Strategies

V. Conclusion

This paper introduces the topology and power sources of the developed fuel cell vehicle. By introducing the fuel cell degradation rate, the time-varying instantaneous hydrogen consumption and efficiency models of the power sources were established, then this paper proposed a dual-mode energy management strategy for energy consumption and efficiency comprehensive optimization. In this paper, the proposed strategy DMDEE is compared with the PMP and PF strategies under two SOC initial states. It shows that when the hybrid system is running at OPM set by the energy management strategy, the energy consumption of the proposed strategy is similar to the approximate theoretical optimal value (under PMP strategy), moreover the fuel cell efficiency can be significantly improved; When the hybrid system is operated at SRM set by the energy management strategy, compared with the PF strategy, the proposed strategy has significant optimization effect on the energy consumption on the basis of same SOC regression tendency; compared with the PMP strategy, the energy consumption of the strategy is increased, but the fuel cell efficiency is improved, and the SOC change trend is more reasonable. In addition, due to the hysteresis control is designed, the frequent switching between operating modes is avoided in this paper. At last, the effectiveness and superiority of the proposed energy management strategy in this paper has been verified in this paper.

Tab. 5 All Results Under Three EMS With Different Initial SOC

<table>
<thead>
<tr>
<th>Initial SOC</th>
<th>0.60</th>
<th>0.80</th>
</tr>
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<tbody>
<tr>
<td>EMS</td>
<td>PMP</td>
<td>DMDEE</td>
</tr>
<tr>
<td>the Whole</td>
<td>65.1g</td>
<td>68.7g</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>(Theoretical Optimale Value)</td>
<td>(Theoretical Optimale Value)</td>
</tr>
<tr>
<td>Consumption</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel Cell</td>
<td>0.4205</td>
<td>0.4312</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Efficiency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOC End Value</td>
<td>0.6000</td>
<td>0.5852</td>
</tr>
</tbody>
</table>

REFERENCES


