Research on Energy Management Strategy Based on Fuel Cell Health Status

Xueshuang Ren, Xin Zhang*, Dewang Liu and Qinyang Lv

School of Beijing Jiaotong University, Beijing 100044, China

*Corresponding author: xinzhang@bjtu.edu.cn

Abstract. Energy management control strategy is one of the key technologies in the development of extended-range fuel cell vehicles. During the use of vehicles, fuel cell performance will decline, which limits the power output of the stack and the life of the stack. In order to control the power output of the fuel cell more reasonably, in this paper, the lumped parameter model of fuel cell is built based on Matlab/Simulink, and the vehicle model is built by AVL/Cruise simulation software. Combined with the fuel cell health state (SOH: State of Health) estimation method, the vehicle demand power and the state of charge (SOC: State of Charge) value of the power battery are used as input, and an energy management control strategy architecture based on the performance degradation of the fuel cell is designed. The simulation results show that the designed energy management can improve dynamic performance, and avoid frequent start and stop of the fuel cell, prolong the service life of the fuel cell, and further improve the economy of the vehicle.

Keywords: Proton exchange membrane fuel cell, Health status estimation, Performance degradation, Energy management strategy

1. Introduction

In recent years, personal mobility has increased and the auto industry has become one of the world's largest economic forces, contributing to global economic growth. At the same time, the use of automobiles has caused a series of major problems. Among them, the society is most concerned about the two major problems are environmental problems and energy problems. Extended-range fuel cell vehicles use hydrogen fuel, and the products are pollution-free and the hydrogen resources are abundant. However, due to the influence of variable load, temperature, humidity and other factors in the use of fuel cell, the performance of the fuel cell will decline, resulting in insufficient output power of the fuel cell, which will have a certain impact on the dynamic performance of the vehicle. Reasonable energy management strategy can solve this problem. At present, a large number of scholars have conducted in-depth studies on vehicle energy management. Energy management strategies are mainly divided into rule-based energy management strategy and optimization-based energy management strategy [1].

The rule-based energy management strategy has strong practicability and reliability, so it is widely used in automotive engineering [2]. Martinez [3] et al. studied the fuzzy logic control strategy of two degrees of freedom, established the expert uncertainty model, and proved the general applicability of this strategy in automotive engineering through experiments. Ridong Z [4] et al. studied the
discrimination of driving mode through neural network, and used adaptive fuzzy control strategy to carry out energy management in combination with vehicle demand power. Liu Nan [5] et al. proposed the Z-curve method and PI adjustment method, and applied this method to the power following strategy, and then carried out simulation tests. Li Qi [6] et al. proposed a fuzzy control theory strategy, the input of the strategy was the SOC and the vehicle demand power, and the output was the fuel cell output power, then the practicability and reliability of the strategy were verified by simulation.

Optimization-based energy management strategies can be divided into global optimization and instantaneous optimization [7]. Energy management strategy based on global optimization is to optimize the target parameters through appropriate control algorithm. Gou Huadong et al. [8] used the fuel consumption matrix and the reachable state set calculation method through the dynamic programming algorithm, and took the minimum fuel consumption as the objective parameter to carry out the optimal energy allocation. Xu Liangfei et al. [9] proposed a model of instantaneous hydrogen consumption, which made the hydrogen consumption expressed by the power consumed, and then obtained the optimal solution of hydrogen consumption. Garcia P [10] et al. proposed a strategy of minimum equivalent hydrogen consumption for hybrid vehicles and applied it in fuel cell trams. Hong Zhihu et al. [11] proposed an energy management strategy capable of braking recovery, this strategy uses dynamic power factor to improve the minimum control strategy of instantaneous equivalent fuel consumption, so as to keep the SOC of the power battery constant.

To sum up, the user can be used according to their own conditions and purpose to select the appropriate energy management strategy. Considering that the health state of the fuel cell affects the power performance of the vehicle, a rule-based energy management strategy is selected in this paper. Aiming at this problem, the finite state machine is improved to make the power performance of the vehicle not affected and the durability of the fuel cell is improved.

2. Lumped parameter model of fuel cell

Since the lumped parameter model is not affected by space and has high accuracy, the lumped parameter model of proton exchange membrane fuel cell (PEMFC) will be established in this paper. The equivalent circuit of fuel cell can reflect the characteristics of fuel cell, and the equivalent circuit of fuel cell is shown in Fig. 1 [12].

![Figure 1. Equivalent circuit model of PEMFC](image)

In the process of chemical reaction, fuel cells will produce irreversible loss, namely overvoltage. The three types of overvoltage are activation overvoltage, ohmic overvoltage and concentration overvoltage [13]. The output voltage of PEMFC is shown in (1) [14].

\[
V_{cell} = E_{Nernst} - \eta_{act} - \eta_{ohm} - \eta_{con}
\]

Where, \(E_{Nernst}\) is the thermodynamic electromotive force, a simplified expression can be obtained from the equation of hydrogen and oxygen fuel cell [15]:
\[ E_{\text{Nernst}} = 1.229 - 8.5 \times 10^{-4} \times (T - 298.15) + 4.308 \times 10^{-2} \times T \times \left( \ln p_{H_2} + 1/2 \ln p_{O_2} \right) \] (2)

Where, \( T \) is the working temperature of PEMFC; \( p_{H_2} \) is the partial pressure of hydrogen; \( p_{O_2} \) is the partial pressure of oxygen;

Where \( \eta_{\text{act}} \) is the activation overvoltage, which is used to activate the electrochemical reaction. The empirical model can be obtained from literature [16]:

\[ \eta_{\text{act}} = \xi_1 + \xi_2 T + \xi_3 \ln(C_{O_2}) + \xi_4 T \ln i \] (3)

Where, \( \xi_1, \xi_2, \xi_3 \) and \( \xi_4 \) are empirical values related to kinetics, thermodynamics and electrochemistry. Generally applicable values are selected in this paper [17], \( i \) is the fuel cell current, \( C_{O_2} \) is the oxygen concentration at the cathode gas interface.

Where \( \eta_{\Omega} \) is ohmic overvoltage, which is generated by the impedance received during the movement of protons in electrolyte and electrons in electrode [18], and its expression is:

\[ \eta_{\Omega} = iR_{\text{ohm}} = i(R_m + R_c) \] (4)

Where \( R_{\text{ohm}} \) is the ohmic internal resistance; \( R_c \) is the impedance that obstructs the passage of electrons through the membrane; \( R_m \) is the impedance of the proton exchange membrane.

Where \( \eta_{\text{con}} \) is concentration difference overvoltage, which is the concentration difference overvoltage caused by insufficient supply of reaction gas in the condition of high current density, and its expression is:

\[ \eta_{\text{con}} = -B \ln \left( 1 - \frac{J}{J_{\text{max}}} \right) \] (5)

Where \( B \) is constant and is related to the working state of the battery, \( J \) is the actual current density, \( J_{\text{max}} \) is the maximum current density.

Table 1. The Fuel Cell Parameter Values

| Parameter | Values | unit |
|-----------|--------|------|
| \( T \)   | 348.15 | K    |
| \( C \)   | 3      | F    |
| \( \xi_1 \)| -0.9514| /    |
| \( \xi_2 \)| 0.0312 | /    |
| \( \xi_3 \)| 7.4 \times 10^{-5} | /   |
| \( \xi_4 \)| 1.87 \times 10^{-4} | /  |
| \( A \)   | 232    | cm^2 |
| \( J_{\text{max}} \)| 2      | A/cm^2 |

3. Extended range fuel cell vehicle model

Based on the above fuel cells lumped model, this paper set up a program model of fuel cell vehicle, the
system configuration is shown in figure 2. The power battery is directly connected with the power bus, fuel cells and DC/DC converter in series. The fuel cell and the power cell are connected to the power bus in parallel, fuel cell and power battery can provide energy to drive motor. The basic parameters of the model is shown in Table 2.

![Extended-range Fuel Cell Vehicle System Configuration](image)

**Figure 2.** Extended-range Fuel Cell Vehicle System Configuration

| Project       | Unit | Values |
|---------------|------|--------|
| long          | mm   | 4770   |
| wide          | mm   | 1830   |
| high          | mm   | 1505   |
| The wheelbase | mm   | 2775   |
| Curb weight   | kg   | 1800   |
| The rolling radius | m  | 0.324 |
| Rolling resistance coefficient | /    | 0.01   |
| Windward area | m²   | 2.204  |

**Table 2.** The basic structure parameters of the vehicle

4. **Energy management strategies based on performance degradation estimation**

4.1. **Overall framework of energy management strategy**

The design of energy management system based on fuel cell performance degradation consists of two main parts: fuel cell health state estimation(SOH) part and finite state machine energy management strategy part. Firstly, combined with the current power of the power cell and the demand power of the vehicle, the output power theoretically required by the fuel cell is given by the finite state machine module. Secondly, the output power reduced by the performance degradation of the fuel cell is estimated during the use process. Finally, the required output power of the power battery is calculated. The energy management control strategy architecture diagram designed in this paper is shown in Figure 3.
4.2. Fuel cell performance degradation estimation
Untracked Kalman filter (UKF) algorithm can estimate the nonlinear system model, has good robustness and accuracy, and can realize the online estimation of fuel cell SOH. Therefore, UKF algorithm has been widely used in many fields [19]. In this paper, based on the fuel cell model, the Ohmic resistance of the fuel cell is estimated by using the untracked Kalman filter algorithm. UKF algorithm refers to the nonlinear equation of state variables of the probability density distribution of approximation. The extended kalman filter in dealing with nonlinear systems need to linear system, lay down higher-order thinking, thus affecting the accuracy of the system. The UKF algorithm does not need to linear system, but with no trace transform method, thus to avoid the down error resulting from high order term, improve the accuracy of the system, and using the process is not complicated, reduces the calculation difficulty. The use process of UKF algorithm is shown in Figure 4:

4.3. Energy management strategies based on fuel cell performance degradation
This paper adopts an energy management strategy based on the performance degradation of the fuel cell, whose state is shown in Table 3, it has the following advantages:

(1) In each state, the power battery will provide the part of the energy that the fuel cell output power is insufficient due to the performance decline. Therefore, the dynamic performance of the vehicle is guaranteed.
(2) The power battery is in the state of low power and moderate power, even if the vehicle power demand is in the braking state, fuel cells did not shut down, but the output minimum fuel cell power, avoid the frequent start-stop effects on fuel cell state of health.

(3) In states 7, 8, 13 and 14, the fuel cell is within the optimal output power range, which improves the fuel utilization rate and thus improves the economic performance of the vehicle.

(4) Whether the power battery is in the state of low or high power, this strategy can try to restore the SOC to its moderate state, so as to avoid the irreversible damage caused by the overcharge or overdischarge of the power battery.

Among them, $P_R$ represents the required power of the vehicle, $P_{FC}$ represents the theoretical output power of the fuel cell, $P_{FC_{min}}$ represents the minimum output power, $P_{FC_{max}}$ represents the maximum output power, and $P_{FC_{opt}}$ represents the best output power of the fuel cell, $P_B$ represents the basic charging power of the power battery. According to the SOC, the power battery can be divided into three parts: low power, moderate power and high power. Combined with the power demand of the whole vehicle, it can be divided into 15 working state modes.

| SOC | $P_R$ | $P_{FC}$ | $P_B$ |
|-----|-------|----------|-------|
| 1   | $P_R \leq 0$ | $P_{FC_{min}}$ | $-P_{FC_{min}} + \Delta P_{FC}$ |
| 2   | $0 < P_R \leq P_{FC_{max}} - P_{B_{opt}}$ | $P_{FC_{opt}}$ | $P_R + P_{B_{opt}} - P_{B_{opt}} + \Delta P_{FC}$ |
| 3   | $P_{FC_{max}} - P_{B_{opt}} < P_R \leq P_{FC_{max}}$ | $P_R$ | $\Delta P_{FC}$ |
| 4   | $P_R > P_{FC_{max}}$ | $P_{FC_{max}}$ | $P_R - P_{FC_{max}} + \Delta P_{FC}$ |
| 5   | $P_{FC_{min}} < P_R \leq P_{FC_{opt}}$ | $P_{FC_{min}}$ | $P_R - P_{FC_{min}} + \Delta P_{FC}$ |
| 6   | $P_{FC_{opt}} < P_R \leq 3P_{FC_{opt}}/2$ | $P_{FC_{opt}}$ | $P_R - P_{FC_{opt}} + \Delta P_{FC}$ |
| 7   | $3P_{FC_{opt}}/2 < P_R \leq 3P_{FC_{max}}/2$ | $2/3P_R$ | $1/3P_R + \Delta P_{FC}$ |
| 8   | $P_R > 3P_{FC_{max}}/2$ | $P_{FC_{max}}$ | $P_R - P_{FC_{max}} + \Delta P_{FC}$ |
| 9   | $P_R \leq 0$ | $P_{FC_{max}}$ | $P_R + \Delta P_{FC}$ |
| 10  | $0 < P_R \leq P_{FC_{min}}$ | $P_{FC_{max}}$ | $P_R - P_{FC_{min}} + \Delta P_{FC}$ |
| 11  | $P_{FC_{min}} < P_R \leq P_{FC_{opt}}$ | $P_{FC_{min}}$ | $P_R - P_{FC_{min}} + \Delta P_{FC}$ |
| 12  | $P_{FC_{opt}} < P_R \leq 2P_{FC_{opt}}/3$ | $P_{FC_{opt}}$ | $P_R - P_{FC_{opt}} + \Delta P_{FC}$ |
| 13  | $P_{FC_{opt}}/3 < P_R \leq 3P_{FC_{max}}/2$ | $2P_{FC_{opt}}/3$ | $1/3P_R + \Delta P_{FC}$ |
| 14  | $P_R > 3P_{FC_{max}}/2$ | $P_{FC_{max}}$ | $P_R - P_{FC_{max}} + \Delta P_{FC}$ |

5. Analysis of simulation result

Take NEDC as the test condition, and perform simulation analysis based on Matlab/Simulink. Figure 5 shows the comparison between the actual vehicle speed and the target vehicle speed obtained. From the figure, it can be found that the actual vehicle speed is basically consistent with the target vehicle speed.
When the initial value of the power battery in the state of moderate power, the simulation results are shown in Figure 6. As can be seen from the figure, when the demand power of the vehicle increases slightly but is less than the optimal output power of the fuel cell, the fuel cell provides energy for the driving motor and changes from state 5 to state 6. In the period of 848–885 seconds and 998–1024 seconds, the fuel cell only works at its best working efficiency point, which ensures the fuel cell’s use efficiency. In state 8, the fuel cell only provides 2/3 of the required power of the vehicle, which ensures that the fuel cell is close to its optimal operating range.

5.1. Analysis of fuel cell performance decline
The initial SOC state of the power battery was set to 60%, and the health state of the fuel cell was simulated and analyzed. In order to study the fuel cell ohmic resistance, set up 10 times NEDC cycle conditions are simulated. Fuel cell ohmic resistance changes as shown in figure 7, fuel-cell ohm resistance showed a trend of gradual increase in the ohmic resistance range 0.01Ω–0.0312 Ω.
In order to compare the fuel cell under ideal state and the decline of the performance, the difference of power battery power output, figure 8 for the output power of the power battery comparison chart. It can be seen from the figure that the actual power output of the power battery is greater than that of the fuel cell in the ideal state. At high power output, the difference is obvious, with an increase of 7.3%.

5.2. Simulation results and analysis of dynamic performance

Fig. 9 shows the acceleration performance curves of FC under ideal state and performance degradation state. Through comparison, it can be seen that the energy management strategy based on fuel cell performance degradation has a 0-50km/h acceleration time of 6.3s, a 100km acceleration time of 13.6s, and a maximum speed of 155.57km/h. The acceleration time of 0-50km/h is 6.47s, the 100km acceleration time is 13.81s, and the maximum speed is 155.5km/h without considering the degradation of fuel cell performance. Fig. 10 is the slope curve comparison diagram. It can be seen from the figure that the maximum slope of the strategy based on FC performance decline is 27.55%, and the maximum slope of the strategy based on FC ideal state is 26.94%.
Figure 9. Acceleration performance curve comparison chart

Figure 10. Climbing curve comparison chart

5.3. Economic simulation results and analysis

Figure 11 shows a comparison between a power follow-based strategy and a fuel cell performance-degrading strategy. As can be seen from the diagram, a NEDC cycle operating conditions. In the power following strategy, the fuel cell started and stopped 21 times in total, and energy management strategy based on FC performance decline, fuel cell power output has a minimum output power, start-stop times is 1. In addition, under one cycle condition, the fuel cell of the power following strategy works in the optimal power output accounting for 14.42% of the whole process, while the fuel cell of the energy management strategy based on fuel cell performance degradation works in the optimal power output can reach 77.19%. Fig. 12 shows the equivalent hydrogen consumption curves under these two strategies. It can be seen from the figure that the equivalent hydrogen consumption of the power following strategy is 4.19kg/100km, and the equivalent hydrogen consumption of the energy management strategy based on fuel cell performance degradation is 4.11kg/100km, and the hydrogen consumption is reduced by 1.9%.
6. Summary
In this paper, the extended-range fuel cell vehicle is taken as the research object, and the fuel cell and vehicle powertrain models are built. The UKF algorithm is used to estimate the ohmic internal resistance of the fuel cell. Combined with the fuel cell health state estimation method, the energy management strategy based on the performance degradation of the fuel cell is designed. Under typical urban conditions in China, the designed energy management strategy was simulated and compared. Through the comparison results, it was found that this strategy could improve the vehicle power performance and reduce the times of fuel cell start and stop, and the fuel cell operating time ratio in the optimal efficiency was increased by 62.77%, and the hydrogen consumption was reduced by 0.08kg/100km.

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