Research on Energy Management Strategy of Vehicle Fuel Cell-Battery Hybrid Energy System Based on GT-SUIT/Simulink

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Abstract. Aiming at a fuel cell electric vehicle, this paper establishes a fuel cell electric vehicle power system simulation platform based on GT-SUIT and Simulink, and proposes a rule-based energy management control strategy. Under the selected European Driving Cycle (NEDC), the simulation results show that the control strategy can effectively distribute energy between the fuel cell and the battery, and meet the power demand of the vehicle. The SOC of the battery is always kept in a reasonable range.

1. Introduction

Fuel cells have the advantages of high energy conversion efficiency, zero or near zero emissions, stable operation and no noise, wide fuel acquisition range, and high reliability. Fuel cells are used as an ideal vehicle energy source\textsuperscript{[1]}. However, a vehicle equipped with only a fuel cell will have the disadvantages of slow power response and long start-up time and no way to recover braking energy. Therefore, the hybrid composition of fuel cells and batteries is an effective technical means to overcome the shortcomings of a single energy source of fuel cells. The energy management strategy of the fuel cell-battery hybrid energy system is the core of vehicle control, that is, to achieve efficient energy distribution between fuel cells and batteries on the basis of meeting the power of the vehicle.

Most scholars have carried out research on vehicle fuel cell-battery hybrid energy systems around energy management control strategies. Xie Xing\textsuperscript{[2]} and others established a vehicle energy management control model based on simulation software Cruise and Simulink, and verified the effectiveness of its energy management control strategy through simulation. Ji Changwei\textsuperscript{[3]} and others based on the simulation software LMS AMESIM realized the stable output of fuel cell voltage through DC/DC converter and realized power distribution by controlling current.

Ji Renhuan\textsuperscript{[4]} proposed a power following control strategy based on fuzzy correction, and further verified the rationality of its strategy with the help of Advisor simulation software. Yu Shuang\textsuperscript{[5]} established a fuel cell power system simulation model based on the Matlab/Simulink simulation platform, and based on the simulation model, respectively carried out simulation verification on the power following energy management method and the equivalent hydrogen consumption energy management method.

Based on the GT-SUIT/Simulink fuel cell electric vehicle co-simulation platform and comprehensively considering the optimal operating characteristics of fuel cell and battery charging and...
discharging characteristics, this paper formulates a rule-based energy management strategy, and conducts simulation verification. The simulation results show that under the premise of meeting the power demand, the energy management control strategy can effectively and reasonably allocate the power of the fuel cell system and the battery under the selected working conditions, which can provide a reference for the development of fuel cell electric vehicles.

2. Materials and Methods

2.1 Fuel cell electric vehicle power system structure
The form of the fuel cell electric vehicle power system studied in the article is shown in Figure 1. The drive motor is used as the power transmission device of the vehicle, and the fuel cell system and the battery are used as the energy source of the vehicle. The function of the DC/DC converter is to convert the output voltage of the fuel cell system to match the bus voltage. The fuel cell system, battery, and DC/DC converter together constitute a vehicle hybrid energy system.

![Fuel cell electric vehicle power system structure](image1)

Fig.1 Fuel cell electric vehicle power system structure

2.2. Fuel cell electric vehicle power system simulation platform

2.2.1. Modeling of vehicle fuel cell-battery hybrid energy system
In this paper, GT-SUIT is used as the simulation software for vehicle power system performance design, which is used to establish a fuel cell electric vehicle fuel cell-battery hybrid energy system simulation platform. The simulation platform mainly consists of fuel cell system, battery, drive motor, DC/DC converter, vehicle and driver, etc. The energy management strategy model of the vehicle fuel cell-battery hybrid energy system is established in Simulink, and GT-SUIT conducts joint simulation.

![Vehicle fuel cell-battery hybrid energy system simulation platform](image2)

Fig.2 Vehicle fuel cell-battery hybrid energy system simulation platform
2.2.2. Fuel cell stack modeling

The fuel cell type used in this article is a proton exchange membrane fuel cell. Its performance characteristics can be clearly described through the output current and voltage characteristic diagram of the fuel cell, which shows the function relationship between the fuel cell output current and the output voltage. The current and voltage output by a fuel cell directly determine the amount of power it releases, and the power output is directly determined by the product of current and voltage [6]. The combined curve of the current-voltage curve and the power density curve is called the polarization curve [7], and the polarization curve can be expressed by the following relationship:

\[ V_{st} = E - V_{\text{activation}} - V_{\text{ohmic}} - V_{\text{concentration}} \]  

In the formula, \( V_{st} \) is the actual output voltage; \( E \) is the theoretical electromotive force; \( V_{\text{activation}}, V_{\text{ohmic}}, \) and \( V_{\text{concentration}} \) are the voltage loss of the electrode surface reaction rate, and the ohmic resistance voltage drop of the proton flow in the electrolyte, and the voltage loss caused by the decrease of gas concentration or the mass transmission of oxygen and hydrogen.

Based on the test bench, the typical operating characteristic curve of the fuel cell system is obtained, as shown in Figure 3.

![Fig.3 Fuel cell system characteristic diagram](image)

2.2.3. Battery modeling

The battery model uses the "equivalent circuit" to describe the basic characteristics of the battery. The equivalent circuit is a network circuit diagram composed of constant voltage source, battery internal resistance, inductance and other components. The attributes of the battery model can be set according to specific needs to obtain different equivalent circuits. The Rint model, which is equivalent to the experimental data, has the characteristics of simplicity, reliability, and high operating efficiency. The equivalent circuit is shown in Figure 4.

![Fig.4 Rint equivalent circuit diagram](image)

The output voltage of the battery can be described as:

\[ U = E - IR \]  

![Image](image)
In the formula, $U$ is the terminal voltage of the battery, that is, the bus voltage of the battery pack; $E$ is the electromotive force of the battery pack, which is also a function of the battery SOC, and can be calculated by interpolating the experimental data; $R$ is the equivalent internal resistance of the battery pack; $I$ is the battery current, a positive value means discharging, and a negative value means charging.

2.2.4. DC/DC converter modeling

The DC/DC converter is the main component of energy distribution in the fuel cell-battery hybrid energy system for vehicles, which control methods are mainly divided into two control methods, current and voltage. The energy management strategy based on current control is adopted in the article. It can not only effectively protect the fuel cell, but also take into account the performance of the battery pack. The fuel economy and system safety of the vehicle are improved[8]. By controlling the output current of DC/DC and then controlling the transition state of the fuel cell system, energy efficient and stable distribution can be realized.

The relationship between the required power of the drive motor, the output power of the battery, and the output power of the DC/DC converter is:

$$P_{\text{bat}} = P_{\text{motor}} - P_{\text{DC/DC}}$$

In the formula, $P_{\text{bat}}$ is the battery output power; $P_{\text{motor}}$ is the drive motor output power; and $P_{\text{DC/DC}}$ is the DC/DC converter output power.

2.3. Energy management strategy of vehicle fuel cell-battery hybrid energy system

The energy management strategy of the fuel cell-battery hybrid energy system for vehicles is based on the basic vehicle status such as accelerator pedal opening, brake pedal opening, vehicle speed, and battery SOC state. On the basis of satisfying the vehicle dynamics, fully considering the battery charging and discharging characteristics and the fuel cell polarization curve characteristics, taking into account the characteristics of driving conditions, the power required by the entire vehicle is reasonably distributed between the fuel cell and the battery, so that The efficiency of the entire vehicle system is optimized.

The energy management control strategy is shown in Figure 5. Among them, $P_{\text{req}}$ is the required power of the vehicle; $SOC$ is the state of charge of the battery; $SOC_{\text{min}}$ is the lower limit of the battery SOC; $SOC_{\text{max}}$ is the upper limit of the battery SOC; $P_{\text{FC}}$ is the fuel cell system output power; $P_{\text{bat}}$ is the battery output power; $P_{\text{FC,min}}$ is the lower limit of fuel cell system output power; $P_{\text{FC,max}}$ is the upper limit of fuel cell system output power; and $P_{\text{FC,opt}}$ is the optimal output power of fuel cell system efficiency.

The energy management control strategy is a control strategy based on logic thresholds, which main power source is the fuel cell system. The control principle for the fuel cell system is to make it fall in the optimal working range. Based on the fuel cell system characteristic curve (Figure 3), the minimum output power $P_{\text{FC,min}}$, the maximum output power $P_{\text{FC,max}}$ and the output efficiency $P_{\text{FC,opt}}$ where the efficiency of the fuel cell system is optimal are calibrated. The output power of the fuel cell system is required to always fall within the range of the minimum output power $P_{\text{FC,min}}$ and the maximum output power $P_{\text{FC,max}}$ of the fuel cell system ($P_{\text{FC,min}}<P_{\text{FC}}<P_{\text{FC,max}}$), and on this basis, the output power of the fuel cell system falls as far as possible at its optimal efficiency. As an auxiliary energy system, the battery plays the role of power balance, and at the same time stores its recovered energy during the braking and deceleration of the vehicle.

The whole vehicle will encounter various situations in actual operating conditions, which are mainly divided into the following three driving conditions: starting conditions, driving conditions (including constant speed, acceleration, and climbing conditions), deceleration/brake conditions[9];

1) Starting conditions

In the process of starting a fuel cell electric vehicle, the fuel cell system requires a certain start-up time and power response. In addition, in the process of vehicle towing, the power at a lower speed can lead to the low efficiency of the fuel cell system. In the starting conditions, the battery provides energy to the fuel cell auxiliary system to start the fuel cell system.

2) Driving conditions
When the required power of the fuel cell electric vehicle is less than its minimum output power $P_{FC-min}$ and the battery $SOC < SOC_{min}$, the fuel cell system is controlled to work at the optimal efficiency, under the conditions of vehicle driving, the remaining energy is used to charge the battery. If $SOC > SOC_{min}$, make the fuel cell system work at the best efficiency, and the fuel cell system will drive the vehicle alone.

3) Braking/deceleration conditions
When the required power of the fuel cell electric vehicle is less than 0, the vehicle enters the braking mode, and the fuel cell system and the battery do not output power. When $SOC < SOC_{max}$, the battery recovers the braking energy. On the contrary, there is no need to activate the braking energy recovery mode.
3. Results & Discussion

3.1. Simulation calculation and result analysis

According to the above vehicle fuel cell-battery hybrid energy system model, Simulink is used to establish the vehicle fuel cell-battery hybrid energy system energy management strategy, which is evaluated and verified based on the GT-SUIT simulation platform. The basic parameters of the vehicle are shown in Table 1.

| Parameter name                  | Parameter value |
|---------------------------------|-----------------|
| Curb quality (m₀/kg)            | 1650            |
| Full load quality (m/kg)        | 2150            |
| Transmission efficiency         | 0.95            |
| Drag coefficient (C₀)           | 0.30            |
| Frontal area (A/m²)             | 2.65            |
| Rolling resistance coefficient  | 0.009           |

The parameters of the vehicle fuel cell-battery hybrid energy system are shown in Table 2. The NEDC cycle mode is selected for this simulation test. The cycle mode is composed of 4 urban cycles and 1 suburban cycle programs, including parking, acceleration, uniform speed, deceleration. And the simulation test time is 1180s.

| The key components  | parameter name                  | Parameter value |
|---------------------|---------------------------------|-----------------|
| Fuel cell system    | rated power (P₀/kw)             | 30              |
|                     | Peak power (P/kw)               | 45              |
| Battery             | Total energy (kw)               | 9.6             |
|                     | Maximum discharge rate (C)      | 8               |
|                     | Maximum charging current (A)    | 85              |
|                     | Maximum discharge current (A)   | 165             |
| DC/DC Converter     | rated power (kw)                | 60              |
|                     | Input voltage (V)               | 0~520           |
|                     | The output voltage (V)          | 120~620         |

It can be seen from Figure 6 that there is a small fluctuation between the actual vehicle speed and the target vehicle speed in the simulation test, which can indicate that the vehicle speed is following well, and it can also indirectly illustrate the accuracy of the model and the control strategy.

![Fig.6 Relationship between vehicle speed and time](image-url)
Fig. 7 Vehicle demand power

Fig. 8 Fuel cell and battery output power

Fig. 9 Battery, fuel cell and DCDC output voltage
It can be seen from Figure 7 that on the basis of meeting the power of the vehicle, the required power of the vehicle is provided by the fuel cell system and the battery. Among them, the fuel cell system, as the main energy system, can output power stably and efficiently, providing most of the power required by the vehicle. As an auxiliary energy system, the battery can assist the fuel cell system to drive the vehicle. In the simulation result, the battery output power contains a negative value, indicating that the braking energy is effectively recovered (Figure 8).

It can be seen from Figure 9 that the output voltage of the fuel cell system is 201.2v~234.1v, which has a large fluctuation range and does not match the bus voltage. After being boosted by the DC/DC converter, its output voltage is about 482.3v, which is consistent with the bus voltage.

It can be seen from the change curve of SOC in the cycle working condition in Figure 10 that the SOC of the battery fluctuates within a reasonable range, ranging from 80% to 72.6%, and the battery does not experience excessive charging and discharging.

4. Conclusions
This article is based on the GT-SUIT simulation platform to model the vehicle fuel cell-battery hybrid energy system. The energy management strategy was built through Simulink, which also evaluated and verified by simulation. The energy management control strategy can reasonably distribute the power distribution between the fuel cell system and the battery under the premise of meeting its power requirements. Through the DC/DC converter, the output voltage of the fuel cell system can be increased to achieve the goal of being consistent with the bus voltage, and the SOC of the battery can be maintained in a reasonable working range. The above shows that the energy management strategy is a feasible and effective solution, which can provide a theoretical basis for the development of vehicle fuel cell-battery hybrid energy system and vehicle.

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