Control Strategy of Plug-in Fuel Cell Hybrid Vehicle Based on Drive Cycle Recognition

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Abstract: A control strategy based on drive-cycle recognition is proposed for the energy management control of plug-in fuel cell hybrid vehicle. Firstly, the drive-cycle recognition fuzzy controller was designed and the battery target SOC was adjusted according to the drive-cycle recognition results; Secondly, with the goal of improving the economy of the vehicle and the durability of the fuel cell, the energy management fuzzy controller and the fuel cell switch controller were designed, energy distribution of dual power source was realized combined with the target SOC control result; Finally, the comprehensive drive-cycle condition was established, the drive-cycle recognition strategy was simulated and verified basing on the MATLAB/Simulink simulation platform. The results show that the strategy achieves a reasonable adjustment to the target SOC of the battery, compared with the power following strategy, the hydrogen consumption is reduced by 7.8%, which reduces the occurrences of factors which affect negatively durability of fuel cell.

1. Introduction

Because of almost no pollution, zero emission and high energy conversion efficiency, the fuel cell vehicles (FCV) have become one important direction of new energy vehicles [1]. But for those FCVs with fuel cell engine as only power source, their dynamics performance and response performance are not as good as other traditional vehicles [2], therefore the Plug-in Fuel Cell Hybrid Vehicle (PFCHV) with fuel cell engine and power battery are becoming new research and development focus. In reference [3], a control strategy model of energy management for fuel cell compensated power battery discharge based on micro-variable fuzzy logic control is proposed to improve economy, basing on efficiency optimization of energy utilization of power system. Lin and et al proposed an optimization feedback control strategy considering fuel cell decay, and get lower energy consumption compared with that of the rule based strategy [4]. Wang Z. presented an energy management strategy for fuel cell bus based on Pontryagin's minimum principle, which taking the minimum hydrogen consumption as the target to control the power of fuel cell, and get better durability and economy than that of the traditional switch mode strategy [5]. Han J. proposed a dynamical planning method with equivalent factor of equivalent consumption minimization strategy for fuel cell hybrid electric vehicles, which can improve economy with predefined driving cycle [6]. Liu Y. conducted research on a multi-objective hierarchical prediction energy management strategy for range extended fuel cell vehicles, which reduces operation cost more effectively than that of the SOC maintenance and ECMS strategy [7]. Xu L. proposed an optimal energy management strategy of fuel cell electric vehicles, which can get better fuel economy.
and durability basing on multi-target optimization under the constrains of fuel cell decay rate and equivalent hydrogen consumption\(^{[8]}\).

In the PFCHVs, the power battery is the main power source. If the energy control strategy make the power battery recharged and discharged in larger amount and frequently, which can cause some negative effect to battery life. And if the SOC of battery are limited in higher efficiency area, which cannot make good use of the electricity energy in battery. In order to improve this battery. In order to improve this condition, the control strategy of plug-in fuel cell hybrid vehicle based on drive-cycle recognition was adopted to conduct research. To use more electric energy from grid and reduce hydrogen consumption, the target SOC should be regulated basing on drive cycle recognition results, which can prolong battery life by controlling the SOC at the high efficiency area under high power needing conditions, and reduce the SOC under lower power conditions. And then taking the improvement of fuel economy and fuel cell durability as target under the requirements of vehicle dynamics, the energy management fuzzy control strategy and fuel cell switch control strategy were formed to manage the energy distribution with consideration of SOC control requirements. Finally, the development of control strategy basing on ADVISOR was conducted, and the energy control strategy was verified by means of simulation.

2. The power system of PFCHV

The sketch of the power system of PFCHV analyzed in this paper was shown in figure 1, its main parts include power battery, fuel cell engine, electric motor and its controller, main speed reducer and differential. And the fuel cell engine can just output energy, and the battery is used to store or output energy which can receive energy from the grid, fuel cell engine and braking energy recuperation.

In the power system, there are three power calculation equations:

\[
\begin{align*}
    P_{\text{req}}(t) &= \eta_m(t) \times P_m(t) \\
    P_{\text{dc}}(t) &= \eta_{\text{dc/dc}}(t) \times P_{\text{fc}}(t) \\
    P_b(t) &= \eta_{\text{dc/ac}} \times [P_m(t) + P_{\text{dc}}(t)]
\end{align*}
\]

where \( P_{\text{req}} \), \( P_m \), \( P_{\text{dc}} \), \( P_{\text{fc}} \), \( P_b \) are the vehicle required power, EM power, DC\text{\textr DC power, fuel cell power and battery power respectively}; \( \eta_m \), \( \eta_{\text{dc/dc}} \), \( \eta_{\text{dc/ac}} \) are the efficiency of EM, DC\text{\textr DC converter, DC/AC inventor respectively.}

3. Energy management strategy basing on drive cycle recognition

The fuzzy control method has advantage of nonlinear, robustness and real time, which has been wildly used in energy management strategy for new energy vehicles\(^{[9,10]}\). For the PFCHVs, the control of battery target SOC(SOC*)can bring a difficulty between the battery life protection and utility of lower cost electric energy. In order to study this problem, an energy management strategy basing on drive cycle recognition was established using fuzzy logic control theory, which is consisted of fuzzy controller for drive cycle recognition, switch controller for fuel cell engine and fuzzy controller for energy management. The fuzzy controller for drive cycle recognition is used to identify the change of drive cycle characteristic parameters, and adjust the SOC* according its recognition
results. The switch controller for fuel cell engine is used to control fuel cell mode basing on vehicle operation condition. The fuzzy controller for energy management is used to control energy distribution basing on power requirement and the difference between current SOC and target SOC*.

![Fig. 2 Sketch for fuzzy control system basing on drive cycle recognition](image)

In figure 2, $V_{ave}$ is the average vehicle speed during sample time; $R_{idle}$ is idle time ratio of sample time; SOC* is target SOC of battery; $P_{req}$ is vehicle required power; $P_{b\text{ max}}$ is maximum output power of battery at current time; $f_{con}$ is switch signal of fuel cell engine; $f_{con\_pre}$ is switch signal of fuel cell engine at former sample time; $P_{fc\_final}$ is the final power requirement for fuel cell engine.

### 3.1 Drive cycle recognition and SOC* regulation

The fuzzy controller for drive cycle recognition is used for regulating SOC* basing on recognition results of drive cycle, which includes fuzzy variable membership function design, fuzzy control rule design and processing of fuzzy controller Output variable.

#### 3.1.1 Variable Selection for input and output.

The selection of drive cycle characteristic parameter should represent drive cycle characters and use as less parameters as possible\[^{11}\]. The average vehicle speed during sample time and idle time ratio during sample time were selected to be drive cycle characteristic parameters, and the temporary parting conditions are taken into consideration in calculation of average speed to avoid the idle time’s influence to average speed. These two characteristic variables are defined as followed:

$$V_{ave}(t) = \begin{cases} \frac{\sum_{i=0}^{t} V(i)}{t-t_0}, & t < T \\ \frac{\sum_{i=T-t}^{T} V(i)}{T-t}, & i \geq T \end{cases}$$

(4)

$$R_{idle} = \begin{cases} \frac{t_0}{t}, & t < T \\ \frac{t_0}{T}, & t \geq T \end{cases}$$

(5)

where, $V(i)$ is vehicle speed at time i; $t$ is running time; $t_0$ is total time with 0 speed during sample period; $T$ is sample period.

According to the practical conditions, the drive cycle of the vehicles can be classified into three kinds, which are city cycle, suburban cycle and highway cycle\[^{12}\]. For design of the fuzzy controller basing on drive cycle, three typical drive cycles were selected to compare their characteristic parameters with statistic results listed in table 1.
Table 1. Characteristic parameters of three typical drive cycles

| Classification | Drive cycle | \( V_{\text{ave}} \) (km/h) | \( R_{\text{idle}} \) (%) |
|----------------|-------------|-----------------------------|--------------------------|
| City           | CLTC-P part1| 20.2                        | 35.2                     |
|                | NYCC        | 17.52                       | 34.9                     |
|                | MANHATTAN   | 17.17                       | 36.06                    |
|                | CLTC-P part2| 38.2                        | 19.8                     |
| Suburban       | UDDS        | 38.82                       | 18.83                    |
|                | WVUSUB      | 34.56                       | 25.15                    |
|                | CLTC-P part3| 53.9                        | 5.6                      |
| Highway        | HWFET       | 78.2                        | 0.7                      |
|                | US06        | 83.29                       | 7.32                     |

According to the statistic results of these three drive cycles, there are apparent differences among their characteristic parameters. From city cycle to highway cycle, their average speed increases, their idle ratio decreases.

3.1.2 Design of drive cycle recognition fuzzy controller. The recognition fuzzy period is set to be 200s, and each drive cycle block is identified independently, then the similarity of each drive cycle block and drive cycle type can be calculated. The domain of discourse of \( V_{\text{ave}} \) is \([0,110]\) with 4 fuzzy subsets. The domain of discourse of \( R_{\text{idle}} \) is \([0,0.8]\) with 5 fuzzy subsets. The domain of discourse of \( \text{SOC}^* \) is \([0.3,0.7]\) with 3 fuzzy subsets. The input and output membership functions are types of combination of “trimf” function and “trapmf” function, as shown in figure 3.

![Membership functions of drive cycle for recognition fuzzy logic](image)

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Fig.3 Membership functions of drive cycle for recognition fuzzy logic

The figure 4 presents the internal resistance curves under charging and discharging conditions of the power battery in this paper. The internal resistance changes apparently with charging and discharging, and it determines charging and discharging efficiency of the battery. The battery has higher efficiency at smaller internal resistance with less thermal loss. In this paper, the \([0.5,0.7]\) is chose as higher efficiency operation range for \( \text{SOC} \), and 0.6 is chose as its highest efficiency point.
Three design rules of the fuzzy controller are listed as following: 1) when the real drive condition is more likely to be the city drive cycle, the SOC* should be decreased to reduce the hydrogen energy consumption, and for charging more electric energy from grid; 2) when the real drive condition is more likely to be the highway drive cycle, the more power required by vehicle, then the SOC* should be controlled at higher efficiency operation range to reduce the hydrogen energy consumption, and save more capacity for charging from grid. Under this condition, the battery can work at higher efficiency with less thermal loss; 3) when the Vave is kept unchanged, the Ridle is higher, this means the drive behavior is more aggressive. Under this condition, the SOC* should be reduced to output more energy from the battery to power the vehicle. The output variable of SOC* of fuzzy controller is shown as figure 5.

![Fig.4 Relation of SOC and internal resistance at changing and discharging](image)

According to the input variable and the rules of fuzzy controller, the Mandani method is used to get the output fuzzy value, it means that the implication operator uses the Minimum method, the combination operator uses Maximum method, and operator uses Minimum method, the centroid method is used to perform defuzzification to get final value of output of SOC*.

### 3.2 The control strategy of power distribution

Energy manage fuzzy controller is for the control of energy distribution basing on the difference between target and real value of SOC, and the change of power requirement of vehicle. Its whole design includes three parts which are design of fuzzy variable membership function, design of fuzzy control rules, and calculation of output variable of fuzzy controller.

#### 3.2.1 The selection of input and output variables

The difference between real SOC and SOC* is selected as input variables with the distribution power of fuel cell selected as output variable. The difference between real SOC and SOC* is calculated using equation (6).

$$\Delta SOC = SOC - SOC^*$$  \hspace{1cm} (6)

The openness of acceleration pedal can reflect power requirement of drive, the required torque can be get according to the openness of acceleration pedal and external characteristic torque corresponding to real rotation speed of electric motor, shown as equation (7).

$$T_{req} = L_{acc} \times T_{m_{max}}(n)$$  \hspace{1cm} (7)

Where $L_{acc}$ is the openness of acceleration pedal; $T_{m_{max}}$ is external characteristic torque of EM; n is real time rotation speed.

The required power of whole vehicle is calculated using equation (8).
\[ P_{\text{req}} = \frac{T_{\text{req}}}{9550} \times \eta + P_{\text{aux}} \]  

(8)

Where \( \eta \) is efficiency of EM; \( P_{\text{aux}} \) is the power consumed by electrical accessories of vehicle.

3.2.2 Design of fuzzy controller for energy management. The output and input membership functions are the combination of “trimf” and “trapmf” function, as shown in figure 6. The domain of discourse of \( P_{\text{req}} \) is [0, 100] with 7 fuzzy subsets; The domain of discourse of \( \Delta \text{SOC} \) is [-0.5, 0.5] with 6 fuzzy subsets; The domain of discourse of \( P_{\text{fc}} \) is [0,50] with 8 fuzzy subsets.

![Membership functions of fuzzy controller for energy management](image)

\[ P_{\text{req}} \]

\[ \Delta \text{SOC} \]

\[ P_{\text{fc}} \]

Fig. 6 Membership functions of fuzzy controller for energy management

![Power-efficiency curve of fuel cell](image)

Fig. 7 Power-efficiency curve of fuel cell

The relationship between the fuel cell power and its efficiency is shown in figure 7. The fuel cell engine can output maximum power to 50kW, and its highest efficiency is 60\% at 20kW. Its efficiency will change with output power changing, and the energy management strategy should controlled the fuel cell operated at its higher efficiency area.
The design of fuzzy controller for energy management should meet these following rules: 1) when the SOC is lower than SOC*, the fuel cell supply the driving power of vehicle and charge the battery according to the \(\Delta SOC\); 2) when the SOC is greater than SOC*, the fuel cell should decrease its output power to reduce hydrogen consumption; 3) when the SOC is approaching SOC*, the fuel cell should be controlled to follow the power requirements; 4) the Pfc should be regulated according to the trend of power requirements to avoid charging or discharging battery with bigger current.

The distribution of the output variable of fuzzy controller, \(P_{fc}\), is shown in figure 8.

\[ P_{req} < 0 \quad Y \]
\[ SOC < SOC^* \quad Y \]
\[ P_{on} \leq P_{fc}(t) \leq P_{fc,max} \]
\[ \Delta P_{fc,min} \leq \Delta P_{fc}(t) \leq \Delta P_{fc,max} \]
\[ SOC < SOC_{max} \quad Y \]
\[ P_{on} \leq P_{fc}(t) \leq P_{fc,max} \]
\[ \Delta P_{fc,min} \leq \Delta P_{fc}(t) \leq \Delta P_{fc,max} \]

where, \(P_{fc,max}\) and \(P_{fc,min}\) are maximum and minimum power value of fuel cell respectively; \(\Delta P_{fc,max}\) and \(\Delta P_{fc,min}\) are the upper and lower limits of power variation for fuel cell.

### 3.3 Switch controller of fuel cell

The switch control of fuel cell depends on SOC, \(\Delta SOC\), \(P_{b,max}\) of fuel cell and other factors, its control logic is shown in figure 9. When the vehicle is in braking state, there is no power requirements. In order to reduce negative effect caused by stop and start operation to fuel cell, the switch state is kept as former state; when the SOC is lower than the SOC*, start the fuel cell; when vehicle required power is greater than the product of current maximum power \((P_{b,max}) \) multiplied by protection factor \((k_b)\), the fuel cell should be turned on. When the SOC reaches the charging threshold \((SOC_{max})\), the fuel cell should be turned off or keep its former state.

\[ P_{fc\_final} = P_{fc} \times f_{on} \]
When the vehicle required power is less than the final output power of fuel cell, the battery should be in the charging state.

4. Simulation and results analysis

The ADVISOR software has been widely used to analyze dynamics, economy and emission performances of the electric vehicles. The simulation model for fuel cell vehicle in ADVISOR was modified to develop control strategy, its top level model was shown in figure 10. The developed control strategy was verified in MATLAB-Simulink simulation platform to test the validity of the energy management strategy using recognition of the drive cycle, and compared with the control strategy using power following method.

The combined drive cycle was formed using random method\[13\], and the simulation analysis was conducted basing on this drive cycle. According to the speed change on the combined drive cycle and the recognition results of the fuzzy controller using drive cycle recognition, the SOC* was adjusted as shown in figure 11. From figure 11, it can be found that the SOC* was controlled at lower value in the city drive cycle, and the SOC* can be controlled at higher efficiency area when the vehicle driven in suburban and highway cycle, which can realize the control target of SOC*.

\[ P_{b_{\text{final}}} = P_{\text{req}} - P_{f_{\text{final}}} \]  \hspace{1cm} (12)

The initial value of SOC was set to 0.8, figure 12 presents simulation results of SOC changing condition under two control strategies with combined drive cycle. From figure 12, it can be found that, in the first city cycle, the balanced power is negative because of higher SOC, and output power of fuel cell is lower under power following strategy. With drive cycle recognition strategy, the fuel cell was kept at off state because that the SOC and vehicle power requirement cannot meet fuel cell starting conditions shown in figure 9. In the followed suburban and highway cycles, the battery was discharged with smaller power and controlled by the power following control strategy, and the SOC approached gradually to the highest efficiency point(0.6); When controlled by the drive cycle recognition control strategy, the SOC decreased firstly to highest efficiency point(0.6), then the SOC was controlled around this point. These two control strategies both can reduce thermal loss at larger power state and made battery operated at higher efficiency area. With decreasing of SOC, and in the last city cycle, the power following strategy could still control the battery operated near the
The highest efficiency point. With the decrease of SOC*, the drive cycle recognition strategy could make good use of energy from the battery to reduce output of the fuel cell.

The cost of construction of the hydrogen filling station and hydrogen transportation make the hydrogen price highly above the price of the electric energy of battery with same energy requirements[14]. The comparison of hydrogen consumption between these two control strategies was shown in figure 13. When controlled using the drive cycle recognition strategy, total hydrogen consumption was 385.09g, which is less by 7.8% than that of strategy using power following method.

**Fig. 12** SOC curve of battery

**Fig. 13** Comparison of hydrogen consumption of two strategies with combined drive cycle

Comparison of power using two control strategies in combined drive cycle was shown in figure 14. The conditions such as greater load change, stop and start, idle, over load are main factors that can cause negative influence to life of fuel cell[15]. From the simulation results, it was found that the control strategy of drive cycle recognition can improve the power change conditions with less altitude than that of power following strategy, and the fuel cell remain operation after the time of 1465s with the idle state. Compared with power following strategy, the strategy using drive cycle recognition method can reduce the occurrences of conditions that cause negative effect to fuel cell life, which can benefit the durability of fuel cell.

**Fig. 14** Comparison of output power under two strategies with combined drive cycle
5. Conclusions
For plug-in fuel cell hybrid electric vehicle, an energy management strategy was developed basing on drive cycle recognition. And the simulation test was used to verify its validity on energy management, the results show: 1) The developed strategy can reasonably regulate the target SOC*, and the SOC* can be kept at higher efficiency area of the battery when drove in highway and suburban cycle, which can protect battery life and improve its working efficiency; in city cycle, it can reduce SOC* with less power requirement, which can reduce the output power of fuel cell can save hydrogen;2) Compared with the power following strategy, the strategy using drive cycle recognition can reduce or even avoid the negative conditions that affect fuel cell life, and this strategy can improve the durability of fuel cell.

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