Energy Management Control of Fuel Cell Electric Bus Basing on Fuzzy Rule

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Abstract. A hybrid fuel cell bus was taken as the research object. Firstly, the structure and characteristics of fuel cell bus power system were introduced, and the power system parameter design was completed according to the vehicle parameters and performance design goals. Secondly, in order to improve the durability of fuel cell and the economy of power system, a three input single output fuzzy energy management control strategy was designed, with the fuel cell power increment selected as the control variable to coordinate control fuel cell power output and change; Finally, the effectiveness of the fuzzy control strategy was verified on MATLAB/Simulink platform, the results showed that the fuzzy control strategy can control the SOC of battery reasonably and effectively, while is better than the power-following energy management strategy in terms of power system economy and fuel cell durability.

Keywords: Fuel cell bus; Power system; Energy management; Durability of fuel cell; Fuzzy control

1. Forward
The fuel cell vehicles (FCV) is the kind of new energy vehicles with promising application, which has higher efficiency, zero emission, lower noise, shorter fueling time, longer range [1]. Because of current FCV technology is still in developing process, if the fuel cell engine (FCE) is used as sole power source in vehicles, its lower dynamic responsibility can cause negative effect to FCE durability [2]. Therefore, most of power systems for fuel cell vehicles are fuel cell engine combined other power sources [3]. Then how to form energy management strategy basing on different power sources is becoming a key problem to be resolved [4].

Currently, there are there main power train structures used in FCVs, which are the combination of FCE- power battery, combination of FCE-Super capacitor, and combination of FCE-power battery-super capacitor. For the combination of FCE and power battery, Ying proposed a FCV control strategy by power prediction basing on referenced SOC linear trajectory [5], which can make better economy and operation adaptability. Wang designed an energy control strategy with lowest hydrogen consumption as target function, and set limit values for fuel cell power and variables, the economy and durability performance are better than those of control strategy with switch mode [6]. For combination of FCE and super capacitor, Carignano and et al presented an energy control strategy basing on short time power prediction, which can improve power output more reasonably and consume less hydrogen than those of ECMS control strategy [7]. For combination of FCE, power battery and super capacitor, Li proposed a layered energy control strategy, which can improve fuel cell efficiency and reduce hydrogen consumption [8].
The power train systems for fuel cell bus were discussed here for control strategy development. The features of several main power train systems used for fuel cell buses were compared, then the combination of FCE and power battery was selected as research topic, and parameters were determined basing on selected power train structure and bus performance targets. Then with consideration that the fuel cell durability is the main problem during its marketing process [9], the protection the fuel cell for its durability and improvement of its economy are chose as design targets, and the output power increment of fuel cell is selected as the control variable to develop fuzzy control strategy with three input and one output parameters, which can realize coordinate control for output power and power increment of fuel cell. At last, the China typical city drive cycle was used in simulation to verify the developed energy management control strategy for fuel cell bus.

2. Power Train System Design for Fuel Cell Bus

2.1. Structure of Power Train System

The power train system is the core of bus, its structure with combination of fuel cell and power battery is showed in figure 1. Its main parts include fuel cell engine, power battery, electric motor and its controller, DC/DC inverter, DC/DC convertor, etc.

![Figure 1. Sketch of power train with combination fuel cell and power battery.](image-url)

This power train mechanism has features as following: 1) the addition of power battery which can store energy from grid to reduce fuel cost; 2) the power battery can assistant fuel cell operation during starting period and reduce the dynamical response requirement for fuel cell; 3) energy management for combined power sources can mitigate adverse effect to fuel cell to improve its durability; 4) the power battery can restore energy during vehicle braking for energy recuperation; 5) this structure can provide higher specific energy and stable voltage than that of structure with FCE and super capacitor; 6) this structure is simple and easy arranged with lower control difficulty and cost, when compared with other two structures.

2.2. Parameters Match for Power Train System

According to the power train structure in figure 1, the parameter match for electric motor, fuel cell and power battery were completed basing on basic parameters in table 1 and performance requirements in table 2 for whole vehicle.

| Item                 | Value           | Item                  | Value          |
|----------------------|-----------------|-----------------------|----------------|
| L×W×H/mm             | 12000×2550×3800 | Front Area/m²        | 7              |
| Curb weight/kg       | 14000           | Wheelbase/mm         | 6100           |
| Gross weight/kg      | 18000           | Wheel radius /mm     | 478            |
| Cd                   | 0.65            | Rolling resistance coefficient | 0.015    |
| Main differential ratio | 7.8            | Transmission efficiency | 0.92     |
Table 2. Dynamics and economy performance requirements of fuel cell bus.

| Item                                  | value  |
|---------------------------------------|--------|
| Max speed/km·h⁻¹                       | ≧ 80   |
| Max gradability f/%                   | ≧ 16   |
| Acceleration time (0~50km·h⁻¹)/s      | ≤18    |
| Pure electric range under city drive cycle/km | ≧ 40   |

2.2.1. EM Parameters. The transmission ratio of fuel cell bus is fixed with only one speed reducer. During the bus running process, the bus speed is direct related with rotation speed of electric motor, and the maximum rotation speed can be calculated according formula (1) basing on maximum speed of bus.

\[ n_{\text{max}} = \frac{v_{\text{max}} \times i_0}{0.377 \times r} \]  

Where, \( v_{\text{max}} \) is maximum speed of bus; \( r \) is wheel rolling radius; \( i_0 \) is main differential ratio.

Substituting corresponding variables with data of table 1 and 2, and the motor top speed is calculated using formula one, the result is \( n_{\text{max}} = 3462.7 \text{rpm} \). In this paper, the motor rotation speed is set to 3700rpm, and its rated rotation speed is 480rpm.

The maximum torque of motor is determined by max gradability of bus, which can be calculated using formula (2).

\[ T_{\text{max}} \times \eta_i \times \frac{i}{r} = mgf \cos \alpha + mg \sin \alpha + \frac{C_D A v_i^2}{21.15} \]  

Where, \( \eta_i \) is transmission efficiency of power train system; \( m \) is gross weight of bus; \( g \) is the gravity acceleration; \( f \) is rolling resistance coefficient; \( \alpha \) is max grade angle corresponding to the max gradability; \( C_D \) is aerodynamics drag coefficient; \( v_i \) is bus speed on the grade with maximum angle.

Substituting corresponding variables with data of table 1 and 2, the max torque is calculated using formula (2), the results is \( T_{\text{max}} = 2116 \text{Nm} \). Considering the design margin, the maximum torque of motor was set to 2300Nm.

According to vehicle operation conditions, the peak power of motor should meet the requirements of maximum bus speed, maximum gradability, and max acceleration. The maximum powers needed for top speed, maximum gradability and maximum acceleration of bus are calculated using formula (3),(4), (5) respectively.

\[ P_{\text{max,1}} = \frac{v_{\text{max}}}{3600 \eta_i} (mgf + \frac{C_D A v_i^2}{21.15}) \]  

\[ P_{\text{max,2}} = \frac{v_i}{3600 \eta_i} (mgf \cos \alpha + mg \sin \alpha + \frac{C_D A v_i^2}{21.15}) \]  

\[ P_{\text{max,3}} = \frac{1}{3600 \eta_i} \left[ \frac{\delta m}{2 \times 3.6 \eta_i} (v_f^3 + v_m^3) + \frac{mgf v_m^3}{1.5} \right] \]  

Where, \( \delta \) is the equivalent coefficient of bus weight, here it is 1.1; \( t_a \) is acceleration time; \( v_f \) and \( v_m \) are
For bus dynamics design, the maximum power of motor should be determined by formula (6).

\[
P_{\text{max}} \geq \max(P_{\text{max}_1}, P_{\text{max}_2}, P_{\text{max}_3})
\]  

After calculation basing on formula (3), (4), (5), (6), the maximum power is \( P_{\text{max}_3} = 199.15 \text{kW} \). Take design margin into consideration, the final maximum motor power is set to 220kW.

2.2.2. Parameter Design for Fuel Cell Engine. In most conditions, the fuel cell bus is operated at lower speed. So the power needed to run the bus at the speed of 50km/h with full load is used as reference to determine fuel cell engine power [10]. Using formula (3) and corresponding data in table 1 and 2, the calculated power is 48.06kW, with consideration of energy loss during conversion and transmission, the maximum power of fuel cell engine is set to 60kW.

2.2.3. Parameters Design for Power Battery. During bus operation, the maximum power of bus is supplied by the combination of fuel cell engine and power battery. Therefore the maximum power of power battery can be calculated using formula (7), which is \( P_{\text{b,max}} = 160 \text{kW} \).

\[
P_{\text{b,max}} = P_{\text{max}} - P_{\text{fc,max}}
\]  

In addition to this maximum power, for ensuring the range of fuel cell, the rated voltage of battery is set to 520V with capacity set to 150AH. The final parameters of power train system are listed in table 3.

| Item          | value          | Item          | value          |
|---------------|----------------|---------------|----------------|
| Rated/Max speed /rpm | 1480/3700      | Max torque/Nm | 2300           |
| Rated /Max power/kW | 110/220        | FC Max Power/kW | 60             |
| Max power of battery/kW | 160          | Battery rated voltage/V | 520           |
| Battery capacity /Ah | 150           | 150           | -              |

3. Energy Management Control Strategy

Fuzzy control is a kind of intelligent method which can simulate human brain to conduct judgement and reasoning, with the advantage of nonlinear, robustness and real timing [11], and many research results have shown this method can be used with good effect in energy management of new energy vehicles [12,13]. In order to improve fuel cell efficiency and durability, a Takagi-Sugeno fuzzy controller with three inputs single output was developed basing on fuzzy control theory. This new control strategy can coordinate the power of fuel cell engine and its changing rate, which can reduce occurrences of negative factors that damage durability of the fuel cell [14,15].

3.1. Select of Input and Output Variables

The operation conditions such as stop/start, idle, over load, and load changing greatly are four main factors that affect durability of fuel cell [16], therefore occurrences of these four conditions should be reduced, and make the fuel cell engine and power battery operated with higher efficiency. The vehicle required power \( P_{\text{req}} \), the output power of fuel cell engine at last moment \( P_{\text{fc, pre}} \) and the SOC of power battery were chose as input variables, the current state of fuel cell engine and the power requirements for it are recognized. Basing on calculation and control needings, the domain of \( P_{\text{req}} \) is set \([0,220]\), the domain of SOC is set \([0.3,0.9]\), the domain of \( P_{\text{fc, pre}} \) is set \([0,60]\). The power change of fuel cell engine, \( \Delta P_{\text{fc}} \), is chose as output variable. According to the selected fuel cell engine and the influence of
durability, the domain of $\Delta P_{fc}$ is set $[-5,5]$.

The power requirement from fuel cell engine can be calculated using formula (8).

$$P_{fc} = P_{fc\_pre} + \Delta P_{fc}$$ (8)

For these input and output variables, the power of fuel cell engine is regulated basing on the identification results of $P_{fc\_pre}$ and controlling of $\Delta P_{fc}$, which make the fuel cell operated within the higher efficiency area, and reduce the occurrence of stop/start, idle and overload conditions. The load changing conditions can also be reduced by the control of $\Delta P_{fc}$.

3.2. Fuzzification of the Input and Output Variables

The membership function of fuzzy controller was designed by combination of ‘trimf’ function and ‘trapmf’ function, the fuzzy distribution of each input and output variables are shown in figure 2. The $P_{req}$ has 8 subsets which are $\{S1, S2, S3, S4, M, L1, L2, L3\}$. The SOC has 3 subsets which are $\{S, M, L\}$. The $P_{fc\_pre}$ has 5 subsets which are $\{S1, S2, M, L1, L2\}$. The $\Delta P_{fc}$ has 7 subsets which are $\{S1, S2, S3, M, L1, L2, L3\}$.

![Membership function of input variable $P_{req}$](image1)

(a) Input variable $P_{req}$

![Membership function of output variable SOC](image2)

(b) Output variable SOC

![Membership function of input variable $P_{fc\_pre}$](image3)

(c) Input variable $P_{fc\_pre}$
From figure 2, it can be found that the domain distribution of fuzzy subsets of each variable is not even. Such as the fuzzy subset divided between 10~30kW of $P_{fc_{pre}}$ is more than other area, which can benefit the identification weather the fuel cell operated at higher efficiency area. The division of $\Delta P_{fc}$ near 0 point is also more detailed for identification of the smaller change of power.

### 3.3. Rule Design of Fuzzy Control

The fuzzy control rules are core of fuzzy controller, which can have a direct influence on the results of controller. The fuzzy control rules are formed by the following criteria:

1. To avoid higher discharging rate of power battery, the fuel cell power change $\Delta P_{fc}$ should be controlled according to the $P_{req}$ and $P_{fc_{pre}}$. When the $P_{fc_{pre}}$ is lower than idle power, the $\Delta P_{fc}$ should be adjusted to make $P_{fc}$ above idle power to reduce idle conditions.

2. When fuel cell power change, $\Delta P_{fc}$, required by vehicle is not urgent, the power change should be reduced to avoid idle conditions happened frequently.

3. When the fuel cell engine in working, its output power should be controlled to avoid unnecessary stop/start and overload conditions.

4. When power battery with current SOC works out of the higher efficiency area, in addition to consideration the relation of $P_{req}$ and $P_{fc_{pre}}$, the $\Delta P_{fc}$ should be increased according to the relation of SOC and high efficiency area.

5. To maintain the SOC in the area of high efficiency, when the power battery with current SOC works in high efficiency area, $\Delta P_{fc}$ should be controlled according to the relation of $P_{req}$ and $P_{fc_{pre}}$ to follow the power requirement to some degree.

6. When the power battery with current SOC works in high efficiency area, the output power of fuel cell engine should be reduced by means of variable control.

7. In addition to meet the requirements of above conditions, the fuel cell should be operated within high efficiency area to the best of its ability.

Basing on these above rules, the relation of input and output of fuzzy controller were shown in figure 3.
4. Simulation Analysis

4.1. Selection of Drive Cycle for Simulation
The China city bus cycle (CCBC) was used in simulation for driving cycle. The energy management control strategy, power train efficiency and durability performance were analyzed basing on simulation using MATLAB/Simulink, the CCBC profile was illustrated in figure 4.

4.2. Comparison and Analysis for Simulation Results
The lower SOC initial state of power battery and ideal SOC initial state were set in simulation conditions, the simulation results were deduced using TISO fuzzy control strategy and power following control strategy respectively, which was used to verify the adaptability of control strategy to drive cycle. The output power when using power following strategy is calculated according to formula (9):

\[ P_{SOC} = \frac{SOC^c - SOC}{0.5 \times (SOC_{max} - SOC_{min})} \times P_{cs,chg} \]  

(9)

\[ P_f = P_{req} + P_{SOC} \]  

(10)
Where, $P_{SOC}$ is the power for charge sustaining of SOC for power battery; $SOC^*$ is target SOC of power battery; $SOC_{\text{max}}$, $SOC_{\text{min}}$ are the upper and lower limits of high efficiency range for power battery respectively; $P_{cs,\text{chg}}$ is the regulating factor for charge sustaining power, namely it is charge sustaining power when SOC reach lower limit of high efficiency.

### 4.2.1. The Initial State of Lower SOC

When the initial value of SOC is 0.4, the control results of SOC of power battery using two different control strategies is shown in figure 5. It can be found that when SOC of power battery is lower than target high efficiency, the SOC was adjusted effectively to target range with these two control strategies. And the TISO control strategy can provide better results for SOC with ending SOC of 0.4541, but power following control strategy end the adjusting process at the SOC of 0.4285.

![Figure 5. SOC of power battery.](image)

When the initial value of SOC is 0.4, the output power changing of fuel cell using two energy control strategies is shown in figure (6). Because of the lower value of initial SOC, the charge sustaining power using power following strategy is bigger with the result calculate from formula (9), which make the fuel cell operate continuously from starting. When the vehicle power requirement is 0, the power from fuel cell was used to charge battery. These two power control strategies can keep the output power of fuel cell above its idle power, which can avoid the frequently stop/start and overloading conditions. But the power changed with bigger amount when using power following strategy, which can cause negative effect to fuel cell durability.

![Figure 6. Output power of fuel cell.](image)

When the initial value of SOC is 0.4, the fuel cell efficiency using two control strategies is presented in figure 7, it shows that the fuel cell efficiency using TISO fuzzy strategy is better than that of using power following strategy.
With initial value of SOC of 0.4, the durability and economy results using two control strategies during one CCBC driving cycle is listed in table 4. The statics results show that these two control strategies both have satisfied control effect for overload time, idle time, and stop/start times. And the TISO strategy can provide better results with fuel cell average efficiency improved by 4.79%, battery efficiency improved by 1.1%, and no occurrence of conditions with bigger load changing.

**Table 4. Comparison of simulation results with initial SOC of 0.4.**

| Item                              | Power following control strategy | TISO fuzzy control strategy |
|-----------------------------------|----------------------------------|----------------------------|
| time of load changed with great amplitude/s | 210                             | 0                          |
| Over load time/s                  | 0                               | 0                          |
| Idle time/s                       | 0                               | 0                          |
| Stop/start times                  | 1                               | 1                          |
| average efficiency of fuel cell   | 0.6543                          | 0.6856                     |
| Average efficiency of power battery | 0.9385                         | 0.9487                     |

**4.2.2. Ideal Initial State of SOC.** With 0.6 as the initial value of SOC, the simulation results of power battery SOC using two control strategies were shown in figure 8. It can be found that these two strategies can control SOC of battery around the ideal value with changing rate less than 1.5%, which can improve battery efficiency and reduce heat productivity of battery.

With initial SOC as 0.6, the output power of fuel cell using two control strategies was presented in figure 9. From this figure, because the SOC of battery is near its target SOC*, the power for charge sustaining calculated basing on formula (9) is very small with the power following control strategy, and the output power of fuel cell is directly related with power requirement of vehicle, it means fuel cell operated with frequent occurrences of idle, stop/start and load change with great amplitude, which make negative influence on durability of fuel cell. On the contrary, The TISO control strategy can
maintain the power of fuel cell above its idle power with smaller power changing, which can avoid unnecessary stop/start and over load conditions.

![Figure 9. Output power of fuel cell engine.](image)

With initial value of SOC at 0.6, the efficiency of fuel cell using two control strategies was illustrated in figure 10. It is clear that the fuel cell efficiency can be maintained above 0.6 using the TISO fuzzy control strategy, and the efficiency points by power following strategy are relative smaller and distributed sparely.

![Figure 10. Efficiency of fuel cell.](image)

When the initial value of SOC is 0.6, the durability and economy performance using two different strategies during one CCBC drive cycle were listed in table 5. The statistical results show that: comparison with power following strategy, the TISO fuzzy control strategy can improve fuel cell efficiency by 13.15%, reduce the occurrences of conditions with great load changing, idle and stop/start time, and battery efficiency is reduced by 1.16%.

| Item                             | Power following strategy | TISO fuzzy strategy |
|----------------------------------|--------------------------|---------------------|
| time of load changed with great amplitude/s | 246                      | 1                   |
| Over load time/s                 | 0                        | 0                   |
| Idle time/s                      | 141                      | 0                   |
| Stop/start times                 | 13                       | 1                   |
| average efficiency of fuel cell  | 0.5924                   | 0.6703              |
| Average efficiency of power battery | 0.9821              | 0.9707              |

5. Summary and Conclusions
The power train system of a fuel cell city bus was chose to be the research topic, and the simulation model was formed to verify two different energy management strategies. For protect durability and
improve efficiency of powertrain system, a TISO fuzzy energy management strategy was developed with power change of fuel cell as the control variable, which can realize coordination control of output power and power change for fuel cell. The simulation results show:

1. When the initial value of battery SOC is lower, this control strategy can regulate effectively SOC to its higher efficiency area; when the initial value of battery SOC is near its ideal value, it can realize the changing rate of SOC within 1.5%, which can benefit improvement of battery efficiency and reduce heat production.

2. Comparison with power following strategy, this fuzzy strategy can avoid negative conditions which reduce fuel cell lifetime and improve durability. It can improve fuel cell efficiency by 4.79% and 13.15% with initial value of SOC at 0.4 and 0.6 respectively.

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