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Investigation and analysis of proton exchange membrane fuel cell dynamic response characteristics on hydrogen consumption of fuel cell vehicle

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ABSTRACT

The number of working points and response speed are two essential characteristics of proton exchange membrane fuel cell (PEMFC). The improper setting of the number of working points and response speed may reduce the life of PEMFC and increase the hydrogen consumption of the vehicle. This paper explores the impact of the response speed as well as the working points of the PEMFC on the hydrogen consumption in the real-system level. In this paper a dynamic model of the PEMFC system is established and verified by experiments. The model is able to reflect the dynamic response process of PEMFC under a series different number of working points and different response speed. Based on the proposed model, the influence of working points and the response speed of PEMFC on the hydrogen consumption in the vehicle under different driving cycles is analyzed and summarized, for the first time, in the open literature. The results highlight that the hydrogen consumption will decreases in both cases that with the increase of working point number and increase of response speed. However, the reduction range of hydrogen consumption trends to smaller and may reach to an optimal level considering the trade-off between the hydrogen saving and the other costs, for example the control cost. Also, with a more complex driving cycle, the working points and response speed have a greater impact on the hydrogen consumption in the vehicle applications.

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Introduction

With the ever-increasing concern on the environmental and climate problems, renewable energy power generation is booming in the world [1,2]. Among them, hydrogen achieves efficient energy storage, improves energy utilization and facilitates transportation, and has diversified sources of production, which make it an important member of renewable energy for power generation [3,4]. Proton exchange membrane fuel cell (PEMFC) is a key technology to convert the chemical energy stored in hydrogen into electrical energy by electrochemical reaction [5,6]. Compared with fossil fuel power generation, PEMFC has the advantages of high energy conversion efficiency, high specific power, fast start-up, and zero greenhouse gas emissions, which makes fuel cell vehicle (FCV) gradually enter the public's vision [7,8]. However, the safety, durability and economy of FCV need to be further improved [9].

At present, some researchers make breakthroughs in improving the performance of FCV by developing new materials and improving the structure of PEMFC [10]. Yinlong Zhu et al. opens up a new avenue to dramatically enhancing catalytic activity of metal oxides for other applications through rational design of structures with multiple active sites, so as to improve the performance of PEMFC [11]. Juan Bai proposed that the molybdenum-modulated cobalt-based nanocatalyst can be tuned with favorable initial surface reconstruction and stabilized active centers to reach optimized oxygen evolution reaction catalysis, so as to improve the reaction speed of PEMFC [12]. However, the development of key materials for PEMFC has entered a bottleneck period. There are also researchers who focus their study on energy management strategies of FCV to improve the performance. Some researchers reduce the number of actual working points of PEMFC to avoid the frequent load change of PEMFC to reduce the life loss of PEMFC. Bogeng et al. Limited the power fluctuation and reduced the number of working point changes to improve the health of PEMFC. Their results are conducive to the stability of power distribution of PEMFC [13]. Tianyuli et al. discussed the energy management of FCV based on multi-objective optimal model predictive control (MOMPC), established a system model including economic model and life model, carried out multi-objective optimization in the framework of MOMPC, reduced the actual working point of PEMFC, finally reduced the life loss of fuel cell, and reduced the cost to the maximum [14]. Liu, Yonggang et al. studied a multi-objective optimization oriented energy management strategy based on rule-based learning for proton exchange membrane FCV. The degradation of PEMFC and power cell is regarded as the objective function and transformed into equivalent hydrogen consumption [15]. Yuan, jingni et al. proposed a layered energy management strategy for plug-in FCHEV based on Q-learning, considering the impact of the load-changing on the aging of PEMFC, and considering the aging of PEMFC at the vehicle level [16]. Yang Zhou et al. used PEMFC power and state of charge (SOC) of the battery to minimize the power fluctuation of PEMFC, expressed the optimization as a quadratic programming problem and solved it with MPC. The results show that the power fluctuation is reduced [17]. At the same time, some researchers limit the power response speed of PEMFC to avoid the overshoot of PEMFC caused by the gas supply lagging behind the load-changing to reduce the life loss of PEMFC. ZhumuFu et al. used a genetic algorithm to optimize the PEMFC considering multiple constraints such as power fluctuation and hydrogen consumption. The proposed energy management system limits the PEMFC power fluctuation to 300 W/s, effectively improving the life of the PEMFC [18]. QingchaoSon et al. proposed a hybrid control scheme based on hybrid droop control and disturbance observer control to achieve a dynamic limit of response speed and prolong the life of PEMFC [19]. Zhen-dongSu et al. introduced the markov chain method to achieve the prediction of driving cycles. By predicting the driving cycles in advance, they adaptively limited the response speed of the PEMFC, reduced the fast load-changing of the PEMFC, and reduced the life loss of the PEMFC [20]. YonggangLiu et al. proposed a global fast charging state planning method based on the expected travel distance only. Vehicle speed information in the predicted range can be used to control the response speed of PEMFC in the predicted range according to the predicted speed and charging state [21]. These studies reduce the lifetime loss of PEMFC by reducing the working point or the response speed of PEMFC. However, the number of working points and the response speed of PEMFC have a significant impact on the life of PEMFC and also on the hydrogen consumption of the FCV. At present, no researchers have summarized and analyzed the rule of this impact.

In order to study the impact of the number of working points and response speed of PEMFC on the hydrogen consumption of FCV at the system level, it is the key to establish an accurate dynamic response mathematical model of PEMFC. Outeiro et al. Used a simulated annealing optimization algorithm to extract voltage model parameters of PEMFC. However, only the load with smooth load change is modeled. Therefore, this model may not be suitable for the dynamic analysis of PEMFC [22]. Salim et al. Discussed the parameter identification of PEMFC superposition model by semi-empirical method with the help of particle swarm optimization algorithm. The model provides the estimation of thermal and electrical parameters of PEMFC. The empirical equation of parameters extracted from the particle swarm optimization algorithm is used to estimate the component voltage including Vac, Vohm, Vcon and Estack. However, this model is only based on experimental data, and can not adapt to complex load changes [23]. Kim et al. Proposed a simplified model to predict the dynamic behavior of PEMFC. The model parameters are estimated based on steady and transient conditions [24]. Haddad et al. Developed a dynamic model for PEMFC cells. The effects of water consumption and humidification rate on water diffusion and membrane humidity were studied. However, this model can not reflect the characteristics of power response very well [25]. In order to make up for the above shortcomings, we use the theoretical knowledge of PEMFC to establish a dynamic response model of PEMFC and carry out the varying load experiments of PEMFC under different number of working points and different response speed to verify the established model.

Based on the established dynamic response model of PEMFC, this paper summarizes and analyzes the influence of

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the number of working points and the response speed limit of PEMFC on the hydrogen consumption of FCV at the system level. The main contributions of this paper are as follows:

1. In this paper, a dynamic response model of PEMFC considering the number of working points and response speed limits is established. The model can simulate the dynamic response characteristics of PEMFC under different number of working points and different response speed limits.

2. In this paper, the experimental platform of PEMFC is built, and the dynamic response model of PEMFC is verified by experiments. The model can follow the experimental results of PEMFC perfectly and ensure the correctness of the model.

3. Based on the established dynamic response model of PEMFC, this paper uses a dynamic programming (DP) algorithm to summarize and analyze the influence of different number of working points and different response speeds of PEMFC on hydrogen consumption of FCV under different complexity driving cycles.

Dynamic response model establishment and experimental analysis of PEMFC

**FCV framework**

Fig. 1 is the vehicle control framework of an FCV. The upper part is the FCV structure studied in this paper. PEMFC is the primary source for charging the power battery and driving the vehicle. It is controlled by a fuel cell control unit (FCU) [26]. The battery provides supplementary power and can also recover energy during braking, monitored by the battery management system. The drive motor drives the FCV and is controlled by the motor control unit. The lower part is the structure of the PEMFC system. The air circuit provides clean air with appropriate flow rate, temperature, pressure, and humidity for the stack. It mainly includes air filter, air compressor, intercooler, humidifier, and throttle. The load-changing process of PEMFC is mainly regulated by the amount of reactant gas [27].

**Dynamic model of PEMFC**

There are complex dynamic processes in PEMFC. These complex dynamic processes often affect the lifetime and vehicle hydrogen consumption of PEMFC. In the process of developing vehicle energy management, it is necessary to consider these complex dynamic processes. Therefore, a dynamic model of PEMFC is established in this paper.

**Air circuit model for PEMFC**

The air pressure change rate of air supply pipeline mainly depends on the compressed air flow rate, cathode inlet air flow rate, and air compressor outlet temperature $T_{cp}$:

$$\frac{dp_{am}}{dt} = \frac{RT_{cp}}{M_{a,atm}V_{am}} (W_{cp} - W_{ca,in})$$  

(1)

where $R$ is the general gas constant; $V_{am}$ is the volume of air supply pipe; $M_{a,atm}$ is the molar mass of air in the atmosphere; $W_{cp}$ is the air mass flow rate at the outlet of the air compressor; $W_{ca,in}$ is the airflow rate at the cathode inlet; $T_{cp}$ is the outlet gas temperature of air compressor.

$$T_{cp} = T_{atm} + \frac{\eta_{cp}}{\eta_{g}} \left( \frac{p_{sm}}{p_{atm}} \right)^{\gamma} - 1$$  

(2)

where $p_{sm}$ and $p_{atm}$ are the gas supply pipeline pressure and atmospheric pressure respectively; $T_{atm}$ is the atmospheric temperature; $\eta_{cp}$ is the efficiency of air compressor; $\gamma$ is the specific heat of air.

Because the air supply pipeline is directly connected with the stack, the pressure difference between them is small. It can be assumed that there is a linear relationship between the cathode inlet air flow rate and the pressure difference:

$$W_{ca,in} = k_{ca,in} (p_{sm} - p_{ca})$$  

(3)

where $k_{ca,in}$ is the flow coefficient, $p_{ca}$ cathode inlet gas pressure.

According to formula (1)-(3), the relation of air pressure change in air supply line can be obtained.

$$\frac{dp_{am}}{dt} = \frac{RT_{atm}k_{ca,in}}{M_{a,atm}V_{am}} \left[ 1 + \frac{1}{\eta_{cp}} \left( \frac{p_{sm}}{p_{atm}} \right)^{\gamma} - 1 \right] \left( W_{cp} - (p_{sm} - p_{ca}) \right)$$  

(4)

where $p_{ca}$ is the inlet pressure of cathode, and its change rate can be expressed as:

$$\frac{dp_{ca}}{dt} = \frac{dp_{ca}}{dt} + \frac{dp_{N_2}}{dt} + \frac{dp_{O_2}}{dt} + p_{sat}$$  

(5)

where $p_{O_2}$ and $p_{N_2}$ are the partial pressures of $O_2$ and $N_2$, respectively; $p_{sat}$ is the saturated vapor pressure as a function of stack temperature $T_{st}$.

According to the law of mass conservation and the ideal gas equation, the dynamic change equation of cathode oxygen and nitrogen is:

$$\frac{dp_{O_2}}{dt} = \frac{RT_{st}}{M_{O_2}V_{ca}} (W_{O_2, in} - W_{O_2, rea} - W_{O_2, out})$$  

(6)

$$\frac{dp_{N_2}}{dt} = \frac{RT_{st}}{M_{N_2}V_{ca}} (W_{N_2, in} - W_{N_2, out})$$  

(7)

where $W_{O_2, in}$ and $W_{N_2, in}$ are the mass flow rates of oxygen and nitrogen entering the cathode, respectively; $W_{O_2, out}$ and $W_{N_2, out}$ are the mass flow rates of oxygen and nitrogen flowing out of the cathode, respectively; $W_{O_2, rea}$ is the mass flow rate of oxygen consumed in the reaction; $V_{ca}$ is the total volume of the cathode; $T_{st}$ is the stack temperature; $M_{O_2}$ and $M_{N_2}$ are the molar mass of oxygen and nitrogen, respectively.

The mass flow rate of each gas entering the cathode is:

$$W_{O_2, in} = \frac{x_{O_2, atm}}{1 + \gamma_{atm}} W_{ca,in}$$  

(8)

$$W_{N_2, in} = \frac{1 - x_{O_2, atm}}{1 + \gamma_{atm}} W_{ca,in}$$  

(9)

where $x_{O_2, atm}$ is the mass fraction of oxygen in the inlet gas, $\gamma_{atm}$ is the humidity of the gas.

The mass fraction of oxygen at the cathode inlet can be obtained from the following equation:
where \( y_{O_2,atm} \) is the volume fraction of oxygen in the air.

The inlet gas humidity is the ratio of water vapor mass to dry air mass:

\[
\phi_{atm} = \frac{M_v}{M_{a,atm}} \frac{\varphi_{atm} P_{atm}}{P_{atm} - \varphi_{atm} P_{atm}}
\]

where \( \varphi_{atm} \) is the relative humidity of inlet gas; \( M_v \) and \( M_{a,atm} \) are the molar mass of water vapor and dry air, respectively. \( M_{a,atm} \) is calculated by the following formula:

\[
M_{a,atm} = y_{O_2,aim} M_{O_2} + \left(1 - y_{O_2,atm}\right) M_{N_2}
\]

The oxygen flow rate is related to the stack current:

\[
W_{O_2, rea} = \frac{n I_{st} M_{O_2}}{4 F}
\]

where \( n \) is the number of cells in the stack; \( I_{st} \) is the output current of the stack.

The flow rates of oxygen and nitrogen at the outlet of the stack are determined by the mass coefficients of oxygen and nitrogen in the gas after reaction:

\[
W_{O_2, out} = \frac{M_{O_2} P_{O_2}}{M_{O_2} P_{O_2} + M_{N_2} P_{N_2} + M_{v} P_{atm}} \frac{C_D A_t P_{atm}}{\sqrt{RT_{st}}} \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma + 1}{\gamma - 1}}
\]

\[
W_{N_2, out} = \frac{M_{N_2} P_{N_2}}{M_{O_2} P_{O_2} + M_{N_2} P_{N_2} + M_{v} P_{atm}} \frac{C_D A_t P_{atm}}{\sqrt{RT_{st}}} \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma + 1}{\gamma - 1}}
\]

where \( C_D \) is the backpressure throttle flow correction coefficient; \( A_t \) is the flow area of the backpressure throttle.

The specific expression of the rate of change of cathode inlet pressure can be obtained from the comprehensive formula (5)-(15):
\[
\frac{dP_{\text{act}}}{dt} = \frac{RT_{\text{f}}}{V_{\text{ca}}} \left[ \frac{1}{1 + e^{\frac{a_{\text{act}}}{RT_{\text{f}}}}} \frac{k_{\text{act}}}{1 + e^{\frac{a_{\text{act}}}{RT_{\text{f}}}}} \right] + \frac{RT_{\text{f}}}{M_{\text{act}}V_{\text{ca}}} \left[ \frac{1}{1 + e^{\frac{a_{\text{act}}}{RT_{\text{f}}}}} \frac{k_{\text{act}}}{1 + e^{\frac{a_{\text{act}}}{RT_{\text{f}}}}} \right] \left( \frac{2}{y + 1} \right) \left( \frac{e^{\frac{a_{\text{act}}}{RT_{\text{f}}}}}{y + 1} \right)
\]

Output voltage model of PEMFC

In order to investigate the dynamic characteristics of PEMFC, the internal activation polarization loss, ohmic polarization loss, and concentration polarization loss are respectively equivalent to activation loss resistance \( R_{\text{act}} \), ohmic loss resistance \( R_{\text{ohm}} \), and concentration loss resistance \( R_{\text{con}} \) \([28]\). The actual output voltage of a PEMFC can be expressed as:

\[
U_{\text{out}} = E - U_{\text{act}} - U_{\text{con}} - U_{\text{ohm}}
\]

where \( U_{\text{act}} \) is the actual output voltage of PEMFC; \( E \) is Nernst electromotive force; \( U_{\text{act}} \) is the activation loss voltage; \( U_{\text{con}} \) is the concentration loss voltage; \( U_{\text{ohm}} \) is the ohmic loss voltage.

The equivalent Nernst electromotive force of PEMFC during power generation is closely related to the working temperature of PEMFC, the partial pressure of hydrogen on the surface of anode catalyst, and the partial pressure of oxygen on the surface of cathode catalyst \([29]\):

\[
E = \frac{RT_{\text{f}}}{2F} \ln \left[ \left( \frac{P_{\text{atm}}}{P_{\text{ca}}(T)} \right)^{\frac{b}{2}} \right] - \frac{\Delta H - TS}{2F}
\]

where \( F \) is the Faraday constant; \( \Delta H \) is the enthalpy change of reactants per unit mass; \( \Delta S \) is the entropy change in the reaction process; \( z \) is the number of electrons transferred per unit reactant.

The activation and concentration voltage loss process of PEMFC can be equivalent to the charge discharge process of capacitor:

\[
U_{\text{act}} = \frac{TBa \ln(I_{b})}{I_{b}} \left( I_{b} - C_{\text{act}} \frac{dU_{\text{act}}}{dt} \right)
\]

\[
U_{\text{con}} = -\frac{RT_{\text{f}}}{2F} \ln \left( \frac{1}{I_{\text{lim}}} \right) \left( I_{b} - C_{\text{con}} \frac{dU_{\text{con}}}{dt} \right)
\]

where \( I_{b} \) is the stack current after load change; \( I_{lim} \) is the stack current at the beginning of load change; \( b \) is the empirical constant; \( I_{\text{lim}} \) is the limiting current of PEMFC.

The ohmic loss voltage can be described by equation (21)

\[
U_{\text{ohm}} = I_{b} \left( \frac{\delta}{\sigma} \right) \frac{\kappa_{T}}{I_{b} T - \frac{\kappa_{T}}{I_{b} \sigma}}
\]

where \( \kappa_{T} \) is the influence constant of temperature on the internal resistance of PEMFC, \( \kappa_{T} \) is the influence constant of current density on internal resistance; \( \delta \) is the thickness of the gas diffusion layer; \( \sigma \) is the ion conductivity; \( A \) is the effective active area of PEMFC.

The output power of PEMFC can be expressed as:

\[
P_{\text{fc}} = U_{\text{out}} \cdot I_{\text{f}}
\]
process, and the maximum error rate between the two curves is less than 4%.

Fig. 4 shows the experimental and simulation results of voltage response during load-changing with 8 working points set. Comparing the obtained curve in Fig. 4(a), it can be seen that during the entire loading process, the simulation and experimental results under low power and medium power are also in good agreement, and the maximum error rate between the two curves is less than 3%. Comparing the curves in Fig. 4(b), it can be seen that the simulation and experimental curves are in good agreement during the entire load shedding process, and the maximum error rate between the two curves is less than 2%. Compared with 16 working points, 8 working points reduce the load-change of PEMFC. This makes the error between experimental and simulation results smaller.

Fig. 5 shows the experimental and simulation results of the voltage response of a PEMFC to continuously load-change during a response speed of 30 kW/s. During PEMFC power from 10 kW to 115 kW at 30 kW/s, the voltage decreases from 312v at 6.8 s, and there is an obvious down rush at 9.3 s. This is due to the shortage of gas in PEMFC due to the fact that the response speed of gas in PEMFC itself is much lower than the sudden change speed of current during large load. The experimental and simulated voltage values are 220 V and 217v, respectively, at 9.3s. The error is within the allowable range. The model can respond to the phenomenon of voltage sag very well. After 9.3s, the voltage response values of both the experiment and the model gradually recover. Upload is completed at 30s, and the voltage reaches a stable value of 246v. During the downloading process of PEMFC power from 115 kW to 10 kW at the speed of 30 kW/s, the voltage starts to rise from 244v at 11.2s, reaches the maximum of 324v at 13.7s, and reaches the stable value of 320v at 40s. The downloading process is different from the uploading process, and there is no shortage of gas supply during the downloading process.
Fig. 6 is the experimental and simulation results of voltage response of PEMFC under continuous load change when the response speed is set at 15 kW/s. When the speed of PEMFC increases from 10 kW to 115 kW at 15 kW/s, the voltage begins to decrease from 312V at 6.8s, and the experimental value fluctuates slightly during the decrease, which does not affect the overall trend. At 12s, there is also an obvious downward rush phenomenon. At 12s, the experimental value and simulation value are 222V and 219V respectively. When the error is within the allowable range, the model can well respond to the phenomenon of voltage overshoot. After 12s, the voltage response values of the experiment and the model gradually rise, and the load lifting is completed by 26s, and the voltage reaches a stable value of 245V.

In the process of load-shedding of PEMFC from 115 kW to 10 kW at the speed of 15 kW/s, the voltage starts to rise from 244V in 11.2s, reaches the maximum value of 322V in 16.9s, and reaches the stable value of 320V in 40s. In this process, the simulation value is basically consistent with the experimental value. It is believed that the simulation results are credible, and the mathematical model established can meet the simulation requirements, which can be further studied.

**Experimental analysis of dynamic response characteristics of PEMFC**

Fig. 7 shows the load-changing process of PEMFC when the number of working points is set at 16. Fig. 7(a) shows the change curve of stack power, stack current, and air compressor current during the load-up test of PEMFC from 10 kW to 115 kW. It can be seen that when the PEMFC is set at 16 working points, the stack current rises from 30 A to 480 A with a width of 30 A. The current can realize transient, and there is no fluctuation and delay in the middle. When the power is 80 kW or above, and the load is large, there have serious fluctuation and delay. This is because the voltage has a down rush phenomenon during the load lifting process, which leads to the PEMFC power can not keep up, and the response is relatively slow. In this process, the current of the air compressor fluctuates seriously when the load power is high. This is because the pressure from the air compressor to the cathode of the PEMFC system needs to go through the humidifier, radiator, and other key components, which makes the current of the air compressor fluctuate when the load is large. Similarly, as shown in Fig. 7(b), in the process of load shedding, the change of power of PEMFC still be delayed under higher load, and the current of the air compressor fluctuates under higher load.

Fig. 8 shows the load-changing process of the PEMFC with 8 working points. Fig. 8(a) shows the change curves of stack power, stack current, and air compressor current during the load-up test of the PEMFC from 10 kW to 115 kW. It can be seen that the PEMFC is set at 8 working points when the load-changing process is completed. Stack current increases from 30 A to 480 A with a 60 A width. Current can
be transient without fluctuation and delay. Power fluctuations and delays occur when the load is large. This is due to voltage down rush during the load-up process, which results in PEMFC power failing to keep up with and its response is slow. In the same process, the air compressor current fluctuates seriously when the load power is high. This is because the PEMFC system passes through key components such as the humidifier radiator during the process of establishing the pressure from the air compressor to the cathode of the stack and causes the air compressor current to fluctuate when the load is high. Also, during the load shedding process is shown in Fig. 8(b), the change in power of the PEMFC is delayed at higher loads, and the air compressor current fluctuates at higher loads.

Fig. 9 shows the load-changing response curve of PEMFC when the response speed is set at 30 kW/s. Fig. 9(a) is the response curve from 10 kW to 110 kW at the speed of 30 kW/s. It can be seen that in the process of 6.8s–9.4s, the power of PEMFC rises rapidly from 10 kW to 98.5 kW, the current of stack rises rapidly from 30 A to 450 A, the rise is relatively stable, and the current of the air compressor rises from 1.46 A to 32.25 A. But overall, it can ensure the stable power output of PEMFC. From 9.4s to 25s, the power of PEMFC increases from 98.5 kW to 110 kW, and the increase becomes slow. It takes
quite a long time for PEMFC to reach the final steady state. Similarly, as shown in Fig. 9(b), when the response speed is set at 30 kW/s, the load of PEMFC starts to drop from 110 kW in 11.3s and drops to 10 kW in 13.8s. In this process, the current of PEMFC still changes smoothly, while the current of the air compressor still fluctuates greatly.

Fig. 10 shows the load-changing response curve of PEMFC with response speed set at 15 kW/s. Fig. 10(a) is the response curve from 10 kW to 110 kW with 15 kW/s response speed. It can be seen that when the response speed is set at 15 kW/s, the characteristics of power response and current response are very similar to that when the response speed is set at 30 kW/s, but when the response speed is set at 15 kW/s, it takes more time to reach the steady state. As shown in Fig. 9(b), the load shedding process with the response speed set at 15 kW/s is the same. Compared with the response speed of 30 kW/s, it takes more time to reach the steady state.

Analysis method of impact of dynamic response characteristics of PEMFC on hydrogen consumption of FCV

As a global optimization approach that solves multi-step optimization problems based on Bellman’s principle of optimality, DP provides a provably optimal energy management strategy through an exhaustive search of all control and state grids [30,31]. Applying DP in investigated power-split FCV configuration is to find the offline optimal control orders and minimum hydrogen consumption. Through the above approach, an optimal benchmark for the impact of dynamic response characteristics of PEMFC on hydrogen consumption of FCV is given.

FCV model building for DP algorithms

Vehicle longitudinal dynamics model

The driving resistance of the vehicle includes four parts: air resistance, rolling resistance, ramp resistance, and acceleration resistance due to overcoming its own inertia [32]. Since the driving cycle studied in this paper does not consider the influence of gradient, the driving power \( P_a \) of the vehicle can be calculated by formula 1.

\[
P_a(t) = v(t) \cdot m \cdot \frac{dv(t)}{dt} + mgc_r + \frac{1}{2} \rho c_w A_f v(t)^2
\]

where \( m \) is the vehicle mass; \( c_r \) is the rolling resistance coefficient; \( \rho \) is Air density; \( c_w \) is the empty resistance coefficient; \( A_f \) is the windward area.

At the same time, the power requirement \( P_d \) on the DC bus should be provided by the power \( P_{fc} \) of the PEMFC and the power \( P_{batt} \) of the lithium battery, which can be expressed in Formulas 24 and 25.

\[
P_d(t) = \eta_{drive} \cdot P_{fc}(t) + P_{batt}(t)
\]

\[
\eta_{drive} = \eta_{DC/AC} \cdot \eta_m
\]

where \( \eta_{DC/AC} \) is the efficiency of DCAC; \( \eta_m \) is the motor efficiency.
Hydrogen consumption model of PEMFC
The efficiency of the PEMFC stack is obtained through experiments, which can be described as a look-up function of PEMFC power and efficiency

\[ \eta_{fc} = f_{fc}(P_{fc}) \]  

(26)

The hydrogen consumption of PEMFC is determined by its power and corresponding efficiency [33]:

\[ M_{fc} = \frac{1}{E_{low H_2}} \int P_{fc} \, dt \]  

(27)

Lithium battery model
The DP oriented lithium battery model does not consider the influence of temperature change and battery aging. In this study, the widely used internal resistance model [34]:

\[ U_{batt} = U_{OC} - I_{batt} \cdot R_{batt} \]  

(28)

\[ I_{batt} = \frac{U_{OC} - \sqrt{U_{OC}^2 - 4R_{batt} \cdot P_{batt}}}{2R_{batt}} \]  

(29)

where \( U_{batt} \) is the battery terminal voltage; \( U_{OC} \) is the battery open circuit voltage; \( I_{batt} \) is the battery current; \( R_{batt} \) is the internal resistance of the battery; \( P_{batt} \) is the battery power. Battery state of charge (SOC) is used to reflect the residual capacity of the battery, which is defined as the ratio of the residual capacity and the maximum capacity

\[ SOC = \frac{Q}{Q_{oc}} \]  

(30)

SOC is calculated by ampere hour integration method:

\[ SOC = \begin{cases} \frac{1}{Q_{oc}} \left( Q_{int} - \frac{1}{3600} \int_0^t \eta_{dis} \cdot I_{batt} \, dt \right), & I \geq 0 \\ \frac{1}{Q_{oc}} \left( Q_{int} - \frac{1}{3600} \int_0^t \eta_{chg} \cdot I_{batt} \, dt \right), & I < 0 \end{cases} \]  

(31)

where \( Q_{int} \) is the initial charge of the battery; \( \eta_{dis} \) is the coulomb efficiency of the battery; \( \eta_{chg} \) is the coulomb efficiency of battery charging.

Driving motor model
The generation efficiency of driving motor is a function of motor speed and torque

\[ \eta_m = f_m(T_m, n_m) \]  

(32)

where \( T_m \) is the torque of the driving motor; \( n_m \) is the speed of the driving motor; \( \eta_m \) is the corresponding efficiency when the output torque is \( T_m \) and the speed is \( n_m \).

2 Problem description of FCV based on DP
State transfer equation
This is a multi-stage decision-making problem. For a multi-stage decision-making process with N stages, the state transition equation can be used to describe [35]:

\[ x(k + 1) = f(x(k), u(k)) \]  

(33)

where \( k \) is the stage of DP; \( x(k) \) is the state vector of stage \( k \). The state variables of FCV are usually power battery SOC and vehicle speed, and the vehicle speed can be obtained in advance through the target driving cycle. Therefore, only power battery SOC is selected as the state variable of the optimal control system in this study. \( u(k) \) is the control variable of stage \( k \). Since the output power \( P_{batt} \) of the power battery can be calculated from Formula 2, the decision variable in this study only includes the output power \( P_{fc} \) of the PEMFC.

From equation (29) and equation (31), the state transfer equation of this study can be obtained:

\[ \text{SOC}(k + 1) = \text{SOC}(k) - \left( U_{OC}(k) - \sqrt{U_{OC}^2(k) - 4R_{batt}(k) \cdot P_{batt}(k)} \right) / (2R_{batt}(k)C_{batt}) \]  

(34)

Objective function
Fuel cell vehicle contains two energy sources, PEMFC, and lithium battery, which can be driven independently or simultaneously [36]. The equivalent hydrogen consumption in each stage is calculated by Eq. (35).

\[ J(x(k), u(k)) = M_{fc}(k) + M_{batt}(k) \]  

(35)

where \( M_{fc}(k) \) is the hydrogen consumption of PEMFC, which is calculated by equation (5); \( M_{batt}(k) \) is the equivalent hydrogen consumption of lithium battery. \( M_{batt}(k) \) is calculated by equation (36).

\[ M_{batt}(k) = \begin{cases} \frac{P_{batt}(k)}{\eta_{dis}} \cdot \frac{M_{fc, \text{avg}}}{P_{fc, \text{avg}}}, & P_{batt}(k) \geq 0 \\ \frac{P_{batt}(k)}{\eta_{chg}} \cdot \frac{M_{fc, \text{avg}}}{P_{fc, \text{avg}}}, & P_{batt}(k) < 0 \end{cases} \]  

(36)

where \( P_{batt}(k) \) is the output power of lithium battery at stage \( k \); \( M_{fc, \text{avg}} \) is the average hydrogen consumption of PEMFC; \( P_{fc, \text{avg}} \) is the average output power of PEMFC; \( \eta_{dis} \) is the battery discharge efficiency; \( \eta_{chg} \) is the battery charging efficiency.

For the whole trip, the total equivalent hydrogen consumption can be expressed as:

\[ J' = \min \sum_{k=0}^{N-1} J(x(k), u(k)) \]  

(37)

Constraint condition
Restricted by the working conditions and the actual working capacity of components, vehicles, batteries, and motors should meet certain constraints, which determine the feasible regions of state variables, control variables and related parameters [37]. In order to investigate the influence of working point and power response speed of PEMFC on energy consumption of PEMFC, the control variable \( P_{fc} \) is constrained to a specific working point, and the response speed of \( P_{fc} \) is constrained. The specific constraint conditions are shown in equation (38):

\[ \begin{cases} \text{SOC}_{\text{min}} \leq \text{SOC} \leq \text{SOC}_{\text{max}} \\ P_{fc} = P_{fc} + P_{batt} \\ P_{batt} = [P_1, P_2, \ldots, P_{n-1}, P_n] \\ \frac{dP_{fc}}{dt} \leq \text{V}_{\text{fc, max}} \\ P_{batt, \text{min}} \leq P_{batt} \leq P_{batt, \text{max}} \end{cases} \]  

(38)
where $\text{SOC}_{\text{min}}$ and $\text{SOC}_{\text{max}}$ is the minimum and maximum limits of the SOC of lithium battery, respectively; $[P_1, P_2, \ldots, P_n, P_{n+1}]$ is the feasible working point of PEMFC; $v_{\text{fc, max}}$ is the maximum response speed limit of PEMFC.

**Impact of dynamic response characteristics of PEMFC on hydrogen consumption of FCV**

To get the general rule of the influence of the number of working points and power response speed of PEMFC on the hydrogen consumption of FCV. In this study, based on the DP algorithm proposed in the third chapter, the simulation is carried out under three typical driving cycles of urban, suburban, and highway. The urban driving cycle in this study is the University of West Virginia urban driving cycle, as shown in Fig. 11(a). The driving cycle lasts 1409s. The maximum speed is 35.8 km/h at 758s. The total power demand of fuel cell vehicle is 2.66 kWh. This driving cycle is better reflected in the vehicle running characteristics in this complex traffic area of the city. The suburban driving cycle in this study is the University of West Virginia suburban driving cycle, as shown in Fig. 11(b). The driving cycle lasts 1665s and reaches the maximum speed of 44.8 km/h at 979s. The total power demand of fuel cell vehicle is 7.04 kWh. This driving cycle better shows the vehicle running characteristics in the suburban. The highway driving cycle is shown in Fig. 11(c) at the University of West Virginia. The driving cycle lasts 1640s. The highest speed of 60.7 km/h is reached at 565s. The total power demand of fuel cell vehicle is 20.19 kWh.

**Urban driving cycle**

Fig. 12 shows the simulation results of the DP algorithm when the number of working points of PEMFC is set at 90, 30, 9, and 3 under the urban driving cycle shown in Fig. 11(a).

In Fig. 12(1), the PEMFC works at a pre-set working point. As you can see in the enlarged view from 496s to 524s, the fewer working points are set, the smaller the frequency of change in the output power of the PEMFC. As indicated by the black line, the output power of the PEMFC is set at 30 kW, 60 kW, and 90 kW. It can be seen that the PEMFC can only jump between the three set working points. Fig. 12(2) is the output power of the power battery, determined jointly by the vehicle demand power corresponding to the driving cycle shown in Fig. 11(a) and the power of the PEMFC. Fig. 12(3) is the SOC curve of the power battery, representing the change in the remaining battery capacity as the output power of the power battery changes. Fig. 12(4) shows the total hydrogen consumption when the number of working points is set at 90, 30, 9, and 3 under the urban driving cycle. $k_p$ is the ratio of the total hydrogen consumption to the change of the number of working points. $k_p$ indicates the extent to which the total hydrogen consumption is affected by the increase in the number of working points. The larger the $k_p$, the greater the impact of the number of working points on the total hydrogen consumption. As the number of working points increases, the $k_p$ decreases. Indicates that when the number of working points increases to a certain extent, the continuous increase of the number of working points has little effect on hydrogen consumption.

Fig. 13 shows the simulation results of the DP algorithm under the urban driving cycle shown in Fig. 11(a), when the number of working points of PEMFC is set at 9, and the power response speed is set at 5 kW/s, 10 kW/s, 15 kW/s, and 20 kW/s respectively.

As shown in Fig. 13(1), the maximum load-changing speed of the PEMFC is limited to a pre-set value. In the range of 496s–524s, the black line is the power of the PEMFC at the 5 kW/s response speed limit, while the blue line is the power of the PEMFC at the 20 kW/s response speed limit. Under the same driving cycle, the power response of PEMFC is slow when the response speed limit is 5 kW/s, whereas it is faster and more frequent when the response speed limit is 20 kW/s. The output power of the power battery in Fig. 13(2) is determined by the vehicle demand power corresponding to the driving cycle shown in Fig. 11(a) and the power of the PEMFC. Fig. 13(3) shows the SOC curve of the power battery, which represents the change of the remaining battery capacity of the power battery as the output power of the power battery changes. Fig. 13(4) shows the total hydrogen consumption with the number of working points is set at 9 and the power response speed is set at 5 kW/s, 10 kW/s, 15 kW/s and 20 kW/s respectively under urban driving cycle. $k_s$ is the ratio of the total hydrogen consumption to the change of the response speed. $k_s$ indicates the extent to which the total hydrogen consumption is affected by the increase in the response speed of PEMFC. The larger the $k_s$, the greater the impact of the number of working points on the total hydrogen consumption. As the number of working points increases, the $k_s$ decreases. Indicates that when the response speed increases to a certain extent, the continuous increase of the response speed has little effect on hydrogen consumption.

Fig. 13 shows the simulation results of the DP algorithm under the urban driving cycle shown in Fig. 11(a), when the number of working points of PEMFC is set at 3, and the power response speed is set at 5 kW/s, 10 kW/s, 15 kW/s, and 20 kW/s respectively.

In Fig. 14(1), in the driving period of 496s–524s, the black line represents the power of PEMFC when the response speed limit is 5 kW/s, and the blue line represents the power of PEMFC when the response speed limit is 20 kW/s. Under the same driving cycle, the power response of PEMFC with response speed limit of 20 kW/s is faster and more frequent than that with response speed limit of 5 kW/s. The output power of the power battery in Fig. 14(2) is determined jointly by the vehicle demand power corresponding to the driving cycles shown in Fig. 11(a) and the power of the PEMFC with the constraints guaranteed. Fig. 14(3) shows the SOC curve of the power battery, which represents the change in the remaining battery capacity as the output power of the power battery changes. Fig. 14(4) shows the total hydrogen consumption with the number of working points is set at 9 and the power response speed is set at 5 kW/s, 10 kW/s, 15 kW/s and 20 kW/s respectively under urban driving cycle. It can be seen from the figure that $k_s$ corresponding to different response speeds at 3 working points has the same trend as that at 9 working points. However, the value of $k_s$ is smaller than that of 9 working points, which indicates that the less the number of working points.
points, the less the effect of response speed on hydrogen consumption.

Suburban driving cycle

Fig. 15 shows the simulation results of the DP algorithm when the number of working points of PEMFC is set at 90, 30, 9, and 3 respectively under the urban driving cycle shown in Fig. 11(b). As shown in Fig. 15(1), compared with the urban driving cycle, the load-changing process of PEMFC in suburban driving cycle is significantly reduced. It can be seen from the enlarged diagram of the load-changing process from 1220s to 1260s that when the number of working points is small, the frequent load-changing of PEMFC is relatively less, and less load-changing process is conducive to reducing the life loss of PEMFC. Fig. 15(2) shows the output power of the power battery, which is jointly determined by the vehicle demand power and the output power of the PEMFC corresponding to the driving cycle shown in Fig. 11(b). Fig. 15(3) is the SOC curve of power battery, which shows the change of the remaining battery capacity of power battery with the change of output power of power battery. Fig. 15(4) shows the total hydrogen consumption when the number of working points is set at 90, 30, 9 and 3 respectively under suburban driving cycle. It can be seen from the figure that kp also decreases with the increase of the number of working points in suburban driving cycle.

When the number of working points increases to 30, the impact of the increase of the number of working points on the hydrogen consumption of FCV is very small.

Fig. 16 shows the simulation results of the DP algorithm under the urban driving cycle shown in Fig. 11(b), when the number of working points of PEMFC is set at 9, and the power response speed is set at 5 kW/s, 10 kW/s, 15 kW/s, and 20 kW/s respectively. As shown in Fig. 15(1), compared with the urban driving cycle, the load-changing process of PEMFC in suburban driving cycle is significantly reduced. It can be seen from the enlarged diagram of the load-changing process from 1220s to 1260s that when the number of working points is small, the frequent load changing of PEMFC is relatively less, and less load-changing process is conducive to reducing the life loss of PEMFC. Fig. 15(2) shows the output power of the power battery, which is jointly determined by the vehicle demand power and the output power of the proton exchange membrane fuel cell corresponding to the working condition shown in Fig. 11(b). Fig. 15(3) is the SOC curve of power battery, which shows the remaining battery capacity of power battery with the change of output power of power battery. Fig. 15(4) shows the total hydrogen consumption with the number of working points is set at 9 and the power response speed is set at 5 kW/s, 10 kW/s, 15 kW/s and 20 kW/s respectively under suburban driving cycle. It can be seen from the figure that ks also decreases with
Fig. 12 — Simulation results with the number of working points set at 90, 30, 9, and 3 respectively under the urban driving cycle.

Fig. 13 — Simulation results with the number of working points is set at 9, and the power response speed is set at 5 kW/s, 10 kW/s, 15 kW/s, and 20 kW/s respectively under the urban driving cycle.
the increase of the response speed in suburban driving cycle. When the response speed increases to 15, the impact of the increase of the response speed increases on the hydrogen consumption of FCV is very small.

Fig. 17 shows the simulation results of the DP algorithm under the suburban driving cycle shown in Fig. 11(b), when the number of working points of PEMFC is set at 3, and the power response speed is set at 5 kW/s, 10 kW/s, 15 kW/s, and 20 kW/s respectively.

As shown in Fig. 17(1), in the driving period of 1220s–1260s, the black line represents the power of PEMFC when the response speed limit is 5 kW/s, and the blue line represents the power of PEMFC when the response speed limit is 20 kW/s. Under the same driving cycle, the power response of PEMFC with response speed limit of 20 kW/s is faster and more frequent than that with response speed limit of 5 kW/s. The output power of the power battery in Fig. 17(2) is determined jointly by the vehicle demand power corresponding to the driving cycle shown in Fig. 11(b) and the power of the PEMFC. Fig. 17(3) shows the SOC curve of a power battery, which represents the change in the remaining battery capacity as the output power of the power battery changes. Fig. 17(4) shows the total hydrogen consumption with the number of working points is set at 3 and the power response speed is set at 5 kW/s, 10 kW/s, 15 kW/s and 20 kW/s respectively under suburban driving cycle. As the number of working points is set at 9, the hydrogen consumption of fuel cell vehicle can not be reduced when the response speed is increased to a certain extent.

Highway driving cycle

Fig. 15 shows the simulation results of the DP algorithm when the number of working points of PEMFC is set at 90, 30, 9, and 3 respectively under the highway driving cycle shown in Fig. 11(c).

As shown in Fig. 18(1), the PEMFC works at a predetermined working point. The less the number of working points is set, the smaller the change frequency of PEMFC output power. As in the driving period of 312s–344s, the black line indicates the output power of PEMFC when the number of working points is set at 3. It can be seen that the PEMFC only jumps between the set working points, and the jumping frequency is small. The power battery has good dynamic characteristics. The output power of the power battery in Fig. 18(2) is determined by the vehicle demand power and PEMFC power corresponding to the working conditions shown in Fig. 11(c). Fig. 18(3) shows the SOC curve of the power battery, showing the change of the remaining battery capacity of the power battery with the change of the output power of the power battery. Fig. 18(4) shows the total hydrogen consumption when the number of working points is set at 90, 30, 9 and 3 respectively under highway driving cycle.
Fig. 15 – Simulation results with the number of working points set at 90, 30, 9, and 3 respectively under the suburban driving cycle.

Fig. 16 – Simulation results with the number of working points is set at 9, and the power response speed is set at 5 kW/s, 10 kW/s, 15kw/s, and 20 kW/s respectively under the suburban driving cycle.
**Fig. 17** – Simulation results with the number of working points is set at 3, and the power response speed is set at 5 kW/s, 10 kW/s, 15kw/s, and 20 kW/s respectively under the suburban driving cycle.

**Fig. 18** – Simulation results with the number of working points set at 90, 30, 9, and 3 respectively under the highway driving cycle.
Fig. 19 shows the simulation results of the DP algorithm under the urban driving cycle shown in Fig. 11(c), when the number of working points of PEMFC is set at 9, and the power response speed is set at 5 kW/s, 10 kW/s, 15 kW/s, and 20 kW/s respectively.

As shown in Fig. 19(1), compared with the urban driving cycle, the load-changing process of PEMFC in highway driving cycle is significantly reduced. It can be seen from the enlarged diagram of the load-changing process from 312s to 344s that when the number of working points is small, the frequent load changing of PEMFC is relatively less, and less load-changing process is conducive to reducing the life loss of PEMFC. Fig. 19(2) shows the output power of the power battery, which is jointly determined by the vehicle demand power and the output power of the proton exchange membrane fuel cell corresponding to the working condition shown in Fig. 11(c). Fig. 19(3) is the SOC curve of power battery, which shows the remaining battery capacity with the change of output power of power battery. Fig. 19(4) shows the total hydrogen consumption when the number of working points is set at 90, 30, 9 and 3 respectively under highway driving cycle.

Fig. 20 shows the simulation results of the DP algorithm under the suburban driving cycle shown in Fig. 11(c), when the number of working points of PEMFC is set at 3, and the power response speed is set at 5 kW/s, 10 kW/s, 15 kW/s, and 20 kW/s respectively.

As shown in Fig. 20(1), in the driving period of 312s–344s, the black line represents the power of PEMFC when the response speed limit is 5 kW/s, and the blue line represents the power of PEMFC when the response speed limit is 20 kW/s. Under the same driving cycle, the power response of PEMFC with response speed limit of 20 kW/s is faster and more frequent than that with response speed limit of 5 kW/s. The output power of the power battery in Fig. 20(2) is determined jointly by the vehicle demand power corresponding to the driving cycle shown in Fig. 11(c) and the power of the PEMFC with the constraints guaranteed. Fig. 20(3) shows the SOC curve of a power battery, which represents the change in the remaining battery capacity as the output power of the power battery changes. Fig. 20(4) shows the total hydrogen consumption with the number of working points is set at 3 and the power response speed is set at 5 kW/s, 10 kW/s, 15 kW/s and 20 kW/s respectively under highway driving cycle.

In order to compare the impact of the number of working points and the response speed of PEMFC on hydrogen consumption of FCV under different driving cycles. In this paper, the dimensions of kp and ks under three conditions are unified according to the ratio of total hydrogen demand under suburban driving cycles to total hydrogen demand under urban driving cycles and the ratio of total hydrogen demand under highway driving cycles to total hydrogen demand under urban driving cycles. The kp after unified dimension is shown in Table 1 and ks is shown in Table 2.

As shown in Table 1, as the driving cycle changes from complex to simple, kp changes from large to small. This shows that the simpler the driving cycle is, the smaller the impact of the number of working points of PEMFC on the hydrogen consumption of the FCV is. As shown in Table 2, when the
number of working point is set to 9, the ks value becomes smaller as the driving cycles becomes simpler. This shows that the simpler the driving cycles is, the less influence the response speed of PEMFC has on the hydrogen consumption of FCV. The same rule applies when the number of working points is set to 3.

### Table 1 – Influence of the number of working points of PEMFC on hydrogen consumption of FCV.

<table>
<thead>
<tr>
<th>Driving cycle</th>
<th>3-9 points</th>
<th>9-30 points</th>
<th>30-90 points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban driving cycle</td>
<td>1.32</td>
<td>0.09</td>
<td>0.035</td>
</tr>
<tr>
<td>Suburban driving cycle</td>
<td>0.90</td>
<td>0.09</td>
<td>0.02</td>
</tr>
<tr>
<td>Highway driving cycle</td>
<td>0.79</td>
<td>0.08</td>
<td>0.007</td>
</tr>
</tbody>
</table>

### Table 2 – Influence of the response speed of PEMFC on hydrogen consumption of FCV.

<table>
<thead>
<tr>
<th>Driving cycle</th>
<th>Number of working points</th>
<th>5kW/s-10 kW/s</th>
<th>10kW/s-15 kW/s</th>
<th>15kW/s-20 kW/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban driving cycle</td>
<td>9</td>
<td>1.05</td>
<td>0.49</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.90</td>
<td>0.45</td>
<td>0.22</td>
</tr>
<tr>
<td>Suburban driving cycle</td>
<td>9</td>
<td>1.01</td>
<td>0.41</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.86</td>
<td>0.40</td>
<td>0.20</td>
</tr>
<tr>
<td>Highway driving cycle</td>
<td>9</td>
<td>0.25</td>
<td>0.10</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.18</td>
<td>0.05</td>
<td>0.01</td>
</tr>
</tbody>
</table>

**Conclusion and further outlooks**

**Conclusion**

In order to study the dynamic response characteristics of PEMFC, we set up an experimental bench for PEMFC, and perform load-changing experiments of PEMFC with different number of working points and different power response speeds. Based on the experimental results, we designed a DP algorithm as a benchmark to explore the impact of the number of working points and power response speed of PEMFC on the hydrogen consumption of FCV and draw qualitative conclusions:

1. Under the same working condition, hydrogen consumption gradually decreases with the increase of the number of working points, and the extent of reduction is smaller and smaller. This is because the increase of the number of working points makes it possible for FCV to have more power distribution possibilities in hydrogen management, which makes FCV tend to be more optimum in hydrogen management. When the number of working points increases to a certain range, it will approach the optimum infinitely.

2. Under the same working condition, hydrogen consumption gradually decreases with the increase of power response speed, and the extent of reduction is smaller and smaller. This is because the output power of the PEMFC is...
better able to keep up with changes in driving cycle as the power response rate increases, and FCV hydrogen management has more possibilities to approach the optimal solution.

3. The number of working points and power response speed of PEMFC have different effects on hydrogen management under different complex driving cycle. The more complex the driving cycle, the greater the impact. This is because the number of working points and power response speed of PEMFC is reflected in the process of dynamic operation of PEMFC. For different complex driving cycle, the number of dynamic processes is different, the more complex the driving cycle, the more dynamic processes.

Further outlooks

This paper only explores the impact of the number of working points and power response speed on the FCV economy. In the future, we will explore its impact on the life of PEMFC. How to comprehensively consider the economy and service life of FCV needs to be further studied. In addition, we will quantify the impact of the number of working points and power response speed of PEMFC on FCV and then design a real-time energy management controller considering the number of working points and the power response speed of PEMFC.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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