Energy management strategy for battery/supercapacitor/fuel cell hybrid source vehicles based on finite state machine

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HIGHLIGHTS

● The management strategy for a battery/supercapacitor/fuel cell system is proposed.
● An optimal oxygen excess ratio control is proposed to maximize the net power.
● The finite state machine method is proposed for power distribution.
● The power capability and state-of-charge of energy devices are fully considered.
● The fuel economy and dynamic property are analyzed.

ABSTRACT

In recent years, fuel cell vehicles have attracted attention for their zero emission and environmental friendship. The sole fuel cell system cannot satisfy the dramatical change of motor power demands. In addition, the power fluctuations will damage the fuel cell stacks and shorten the cycle life of fuel cells. Therefore fuel cell systems are always combined with other energy storage devices like batteries and supercapacitors to increase the power density of the power system and fulfill the load power demands. The management strategy of the hybrid propulsion system is a significant technique for the vehicular power system. In this work, a finite state machine based management strategy is first proposed for both the battery/fuel cell and battery/supercapacitor/fuel cell system. The power capabilities of the battery and supercapacitor have been considered as important parameters in the management strategy. Moreover, an optimal oxygen excess ratio control is presented to maximize the fuel cell output net power. To evaluate the performance of the fuel economy and dynamic property, both the simulations and experimental verifications with the real physical system are given, and the real driving cycle of urban dynamometer driving schedule is utilized. The experimental and simulated results indicate that the proposed method is able to guarantee the required power during most of the driving cycles.

1. Introduction

1.1. Background

The scarcity of fossil fuels and environmental pollution have accelerated the development of future automotive. In recent years, the fuel cell electric vehicles have attracted considerable attention for their zero emission and environmental friendship [1]. The most promising fuel cells to be used in vehicle applications are the polymer electrolyte membrane (PEM) fuel cells because of their lightweight nature, low reaction temperature, and small size [2]. A pure PEM fuel cell vehicle always has several disadvantages. Firstly, the startup time of a pure PEM fuel cell vehicle is long and the power response of the system is slow. Secondly, the energy efficiency of the pure PEM fuel cell vehicle is low when the output power enters in low and high operating regions. Thirdly, it is incapable of energy saving from regenerative braking. To overcome these drawbacks, the PEM fuel cells are always combined with other energy storage devices such as batteries and supercapacitors [3].

The dynamic behavior of Li batteries in hydrogen fuel cell power trains have been investigated in Ref. [4]. Compared with the Pb acid batteries, the Li batteries have better performance on dynamic cycles which give major flexibility in the design and energy management of fuel cell powertrains. In recent years, with the popularity of electric vehicles, development of high performance, safety, and low-cost lithium-ion batteries has become an important trend. The lithium-ion
batteries have higher specific energy density which are good candidates for the vehicle applications. The supercapacitors have higher specific power density and longer lifetime [5,6]. Veneri et al. [7] have investigated the effectiveness of a supercapacitor based hybrid energy storage system. The results show that the supercapacitors can improve the expected battery lifespan. In Ref. [8] Capasso et al. have developed the management strategies for the battery and supercapacitor hybrid energy storage system. Their new control strategies aim to extend battery system durability by reducing transient current by means of supercapacitors.

The battery/fuel cell drive structure is a popular hybrid structure used in vehicle applications. In this structure, the fuel cell system is designed for vehicular propulsion and the battery system is designed to provide supplemental power. The advantage of this structure is that low power and transient response demands are required from the fuel cell system. However, the maintenance cost of the battery system is increased. Moreover, frequent charge and discharge with high rates accelerate the deterioration of the battery system. Therefore the battery/supercapacitor/fuel cell drive structure is developed. Since the supercapacitors have higher specific power density and longer lifetime, the advantages of this structure are that the supercapacitors can provide the peak power and recover braking energy so that the burden of battery and fuel cell system are alleviated, and also prolong the lifespan of the battery system by less charging and discharging. The hybridization of lithium-ion batteries and supercapacitors with the fuel cell system can take the advantages of the two devices and overcome the drawbacks of the sole system.

1.2. Literature review

The management strategy of the hybrid power source system is a significant technique for the vehicular system and there is a rich body of academic literature in this field [9]. In order to meet different load demands, Yu et al. [10] have presented an active power-flow control algorithm by using the optimal control theory. Thounthong et al. [11] have presented an optimal control strategy which pointed out how to avoid fast transition of the energy devices in order to reduce their stress. Li et al. [12] have proposed a strategy based on the fuzzy logic control which has been verified in different driving cycles. In Ref. [13], Li et al. have also presented a power distribution strategy based on a combination of wavelet transform and fuzzy logic control. In Ref. [14], an optimal control strategy is proposed for a city bus with PEM fuel cells. Segura et al. [15] have presented a sliding mode control for a medium power fuel cell system. Hu et al. [16] have discussed the optimal control of an electric bus operated in Gothenburg, Sweden. Different energy devices replacement strategies have been studied and analyzed in the presented framework. Ettihir et al. [17] have presented an optimal tracking method to obtain the best performance of the system. Hannan et al. [18] have presented a feedback control strategy for a battery, supercapacitor, and fuel cell hybrid power sources system. The simulation results show that the proposed control strategy provides efficient and feasible energy management for light electric vehicles. Vahidi et al. [19] have investigated the distribution of current demand between the fuel cell and the bank of supercapacitors by using a model predictive control framework. The control framework can handle multiple constraints of the hybrid system. The supercapacitor system supplements the PEM fuel cell system during fast current transients and alleviates the burden of the fuel cell system. Lopez et al. [20] have employed a rule-based power management system where a low pass filter is used to split the power between the PEM fuel cell and the supercapacitors. The benefits of the energy management strategies with respect to the oxygen starvation prevention and reduction of startups and shutdowns are analyzed. In Ref. [21], Capasso et al. have developed an optimal control strategy for the supercapacitors used in a hybrid energy storage system. The control strategy exploits the off-line solution of a proper isoperimetric problem and aims to dynamically optimize the battery durability by reducing peak current. In Ref. [22], Tribioli et al. have developed a controller for the energy management of a parallel fuel cell/battery vehicle with an onboard fuel processor. The strategy proposed attempts to achieve a real-time sub-optimal solution for minimization of fuel consumption. Wang et al. [23] have proposed a rule-based power distribution strategy for the fuel cell, battery and supercapacitor hybrid power sources system, which has fully considered the criteria of different electrical energy storage systems. Zhang et al. [24] have presented a novel configuration for fuel cell vehicles, where three fuel cell stacks are operated through strategic power management. Each fuel cell stack works only at a fixed operating point and the operation time is shortened via an on-off switching control. Bizon [25] have proposed a real-time optimization strategy for the fuel cell hybrid power system based on load-following control. A new switching strategy for the load-following control and real-time optimization loops is proposed to increase the fuel economy of the system. Bubna et al. [26] have studied the benefits of adding supercapacitors to a fuel cell and battery hybrid transit bus. Simulation results show that the supercapacitors greatly improve the performance such as energy throughput, and energy storage heat generation at comparable cost and weight. The methods mentioned above are effective in energy management. This work combined with the consideration of the behaviors of the energy storage system such as the power capability [27] and system states [28] attempts to develop a distributed energy management system for the hybrid power source system.

1.3. Original contributions

The primary objective of this paper is to develop an energy management framework for the battery/supercapacitor/fuel cell hybrid source vehicular system which comprehensively considers the fuel economy and the behavior of energy storage devices. There are three original contributions of this paper which can be clearly distinguished from the aforementioned works of literature: First, an adaptive PID controller is developed to regular the oxygen excess ratio (OER) to its optimal workspace. The transient behavior of the proposed controller with fast response speed, smaller steady-state error, and smaller overshoot, is superior to the traditional feedforward control. Second, a novel finite state machine (FSM) [29] based energy management strategy is proposed for both the battery/fuel cell and battery/supercapacitor/fuel cell hybrid source vehicular systems. Both the SOC and power capability of the battery and supercapacitor have been considered as important parameters in the proposed strategy. Compared with the fuel cell system with the battery as its only energy storage device, the battery/supercapacitor/fuel cell system based on the presented FSM energy management strategy can fulfill the power demands. Moreover, the power fluctuations in this hybrid structure are smaller than the battery/fuel cell system which extends the life cycles of the fuel cells and batteries. Third, to evaluate the performance of the fuel economy and dynamic property, both the simulations and experimental verifications with the real physical system are given. The hydrogen consumptions of different SOC thresholds have been compared.

1.4. Outline of the paper

The remainder of the paper proceeds as follows. The modeling of the hybrid power source system is introduced in Section 2. In Section 3, the mathematical methodologies of the SOC estimation and power capability prediction are first introduced. Then the OER control based on an adaptive PID algorithm is presented. Finally, the FSM based energy management strategy for the battery/supercapacitor/fuel cell hybrid source vehicular system is proposed. The simulation verifications of the presented methods under dynamic driving cycles are given in Section 4. After that, the experimental verifications with the real physical system are given in Section 5. Finally, the conclusions are summarized in Section 6.
2. Modeling of the hybrid power source system

In this section, the general architectures of the equivalent circuit models under study are first given. Then, the PEM fuel cell model including the stack voltage model, anode model, and cathode model are introduced. Moreover, the vehicle model and the parameters of the DC/DC converter are introduced at the end of this section.

2.1. Model of lithium-ion battery

Different types of equivalent circuit models have been developed for batteries so far [30]. Concerning the model complexity and accuracy, the Thevenin model as a mature model is employed in this work. The architecture of the Thevenin model is shown in Fig. 1(a). Based on the presented equivalent circuit model, the dynamic electrical behavior can be deduced as:

\[
V_p = \frac{V_p}{R_p C_p} + \frac{i_b}{C_p} \\
V_b = V_{ocv}(z) - R_b i_b - V_p
\]

where \( V_p \) and \( V_b \) represent the polarization voltage and terminal voltage, \( V_{ocv}(z) \) represents the battery open-circuit voltage which can be formulated by the function of SOC, \( z \) represents the battery SOC, \( i_b \) represents the battery current, \( R_p \) represents the ohmic internal resistance, \( R_b \) represents the polarization resistance, and \( C_p \) represents the polarization capacitance.

To obtain the model parameters, the regression structure of battery model should be first developed. The discrete state equations of Eqs. (1) and (2) can be deduced as:

\[
V_{b,k-1} = e^{-\Delta t / \tau} V_{b,k-1} - (1 - e^{-\Delta t / \tau}) R_p i_{b,k-1} \tag{3}
\]

\[
V_{b,k} = V_{ocv}(z_k) - R_b i_{b,k} - V_{p,k} \tag{4}
\]

where \( \tau = R_p C_p \).

The regression structure of the battery model can be deduced as:

\[
V_{b,k} - V_{ocv}(z_k) = -R_b i_{b,k} - e^{-\Delta t / \tau} V_{b,k-1} - (1 - e^{-\Delta t / \tau}) R_p i_{b,k-1} = -R_b i_{b,k} + e^{-\Delta t / \tau} (V_{b,k-1} - V_{ocv}(z_{k-1}) + R_b i_{b,k-1}) - (1 - e^{-\Delta t / \tau}) R_p i_{b,k-1} = -R_b i_{b,k} + e^{-\Delta t / \tau} (V_{b,k-1} - V_{ocv}(z_{k-1})) + (e^{-\Delta t / \tau} R_b - (1 - e^{-\Delta t / \tau}) R_p) i_{b,k-1} = \alpha_1 i_{b,k} + \alpha_2 (V_{b,k-1} - V_{ocv}(z_{k-1})) + \alpha_3 i_{b,k-1}
\]

Then the regression algorithms like the recursive least-squares method [31] can be used for identification of the regression parameters including \( \alpha_1 \), \( \alpha_2 \), and \( \alpha_3 \). The relationship between the regression parameters \( \alpha_1 \), \( \alpha_2 \), \( \alpha_3 \) and model parameters \( R_p \), \( R_b \), \( C_p \) can be written as:

\[
\begin{align*}
R_b &= -\alpha_1 \\
R_p &= (\alpha_2 \alpha_3 + \alpha_1) / (\alpha_2 - 1) \\
C_p &= (1 - \alpha_2) / (\alpha_1 \alpha_3 + \alpha_1) \log \alpha_2
\end{align*}
\]

The identification results of the lithium-ion batteries in this study are shown in Table 1.

2.2. Model of supercapacitor

For the supercapacitor, the standard RC model [5] is applied in this work. The model structure of the supercapacitor is shown in Fig. 1(b). The electrical behavior of the supercapacitor can be deduced as:

\[
V_s = \frac{1}{C_m} i_c \\
V_c = V_s - R_c i_c \tag{8}
\]

where \( V_s \) represents the terminal voltage of the supercapacitor, \( V_c \) represents the voltage of the equivalent serial capacitance, \( C_m \) represents the equivalent serial resistance, \( i_c \) represents the current of the supercapacitor.

The recursive parameter identification of the supercapacitor is similar to the battery. The parameter identification results of the supercapacitors used in this work are shown in Table 2.

2.3. Model of PEM fuel cell

2.3.1. Fuel cell stack voltage model

The voltage of the PEM fuel cell stack can be calculated as the product of the number of cells \( N_{cell} \) and the stack voltage \( V_{cell} \) as shown in Eq. (9) [20]. The stack voltage \( V_{stack} \) can be expressed as:

\[
V_{stack} = N_{cell} V_{cell} = N_{cell} (E_{cell} - V_{act} - V_{ohm} - V_{con}) \tag{9}
\]

where \( E_{cell} \) represents the Nernst instantaneous voltage, \( V_{act} \) represents the activation voltage, \( V_{ohm} \) represents the ohmic voltage, and \( V_{con} \) represents the concentration voltage.

In Eq. (9), the Nernst instantaneous voltage \( E_{cell} \) can be calculated as:

\[
E_{cell} = E_{cell}^0 - k_c (T - T_{ref}) - \frac{R_c T}{2F} \ln \left( \frac{p_{H_2} p_{O_2}}{p_{H_2}^0 p_{O_2}^0} \right) \tag{10}
\]

where \( E_{cell}^0 \) is the standard-state reversible voltage \( (E_{cell}^0 \approx 1.229 \text{V}) \), \( k_c \) is the empirical constant, \( T \) is the absolute temperature of the fuel cell, \( T_{ref} \) is the reference temperature, \( R_c \) is the ideal gas constant, \( F \) is the Faraday constant, \( p_{H_2} \) is the water pressure, \( p_{O_2} \) is the oxygen pressure, and \( p_{H_2}^0 \) is the hydrogen pressure.

The expressions of the activation, ohmic and concentration voltages can be expressed as follows:

\[
\begin{align*}
V_{act} &= \frac{R_c T}{2F} \ln \left( \frac{\text{lim}}{\text{act}} \right) \\
V_{ohm} &= R_c \text{ohm} i_{ohm} \\
V_{con} &= \frac{R_c T}{2F} \ln \left( 1 - \frac{\text{lim}}{\text{con}} \right)
\end{align*}
\]

where \( \alpha \) represents the charge transfer coefficient (\( \alpha = 0.5 \)), \( i_{act} \)
represents the current density, \( i_0 \) represents the reaction exchange current density, \( i_{\text{lim}} \) represents the maximum current density, \( R_{\text{ohm}} \) represents the ohmic resistance of the fuel cell.

### 2.3.2. Anode model

The hydrogen pressure can be calculated based on the ideal gas law and mass conservation law as shown in Eq. (12).

\[
\frac{dP_{\text{H}_2}}{dt} = \frac{R_{\text{H}_2} T}{V_{\text{an}}} (q_{\text{in}}^{\text{H}_2} - q_{\text{in}}^{\text{H}_2} - q_{\text{out}}^{\text{H}_2})
\]  

where \( R_{\text{H}_2} \) represents the hydrogen gas constant, \( V_{\text{an}} \) represents the volume of the anode, \( q_{\text{in}}^{\text{H}_2} \) represents the hydrogen input flow, \( q_{\text{out}}^{\text{H}_2} \) represents the hydrogen output flow.

The hydrogen input flow of the anode \( q_{\text{in}}^{\text{H}_2} \) can be deduced as the sum of the hydrogen flow provided from the hydrogen tank \( q_{\text{in}}^{\text{tank}} \) and the hydrogen backflow \( q_{\text{in}}^{\text{bac}} \) as shown in Eq. (13).

\[
q_{\text{in}}^{\text{H}_2} = q_{\text{in}}^{\text{tank}} + q_{\text{in}}^{\text{bac}}
\]  

The reaction flow of the hydrogen \( q_{\text{out}}^{\text{H}_2} \) can be calculated by the Faraday law as shown in Eq. (14).

\[
q_{\text{out}}^{\text{H}_2} = \frac{N_{\text{at}} i_0}{2F}
\]  

where \( i_0 \) represents the fuel cell current.

The hydrogen output flow \( q_{\text{out}}^{\text{H}_2} \) represents the unused hydrogen inside the anode and can be calculated as:

\[
q_{\text{out}}^{\text{H}_2} = K_{\text{H}_2} P_{\text{H}_2}
\]  

where \( K_{\text{H}_2} \) represents the empirical coefficient of the anode.

### 2.3.3. Cathode model

For the cathode, the oxygen pressure can be calculated as Eq. (16).

\[
\frac{dP_{\text{O}_2}}{dt} = \frac{R_{\text{O}_2} T}{V_{\text{cat}}} (q_{\text{in}}^{\text{O}_2} - q_{\text{in}}^{\text{O}_2} - q_{\text{out}}^{\text{O}_2})
\]  

where \( R_{\text{O}_2} \) represents the oxygen gas constant, \( V_{\text{cat}} \) represents the volume of the cathode, \( q_{\text{in}}^{\text{O}_2} \) represents the oxygen input flow, \( q_{\text{out}}^{\text{O}_2} \) represents the oxygen output flow, \( q_{\text{out}}^{\text{O}_2} \) represents the oxygen output flow.

The reaction flow of the oxygen \( q_{\text{out}}^{\text{O}_2} \) can be calculated by the Faraday law:

\[
q_{\text{out}}^{\text{O}_2} = \frac{N_{\text{at}} i_0}{4F}
\]  

The oxygen output flow \( q_{\text{out}}^{\text{O}_2} \) can be calculated by Eq. (18):

\[
q_{\text{out}}^{\text{O}_2} = K_{\text{O}_2} P_{\text{O}_2}
\]  

where \( K_{\text{O}_2} \) represents the empirical coefficient of the cathode.

The parameters of the fuel cell are listed in Table 3.

### 2.4. Model of the DC/DC converter

In this work, an efficient map is developed to describe the operational behavior of the DC/DC converter. The efficient map of the DC/DC converter is shown in Table 4.

### Table 2

<table>
<thead>
<tr>
<th>SOC (%)</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_i ) (mΩ)</td>
<td>3.137</td>
<td>3.137</td>
<td>3.122</td>
<td>3.122</td>
<td>3.085</td>
<td>3.137</td>
<td>3.050</td>
<td>3.050</td>
<td>3.025</td>
</tr>
<tr>
<td>( C_m ) (F)</td>
<td>2809.6</td>
<td>2880.5</td>
<td>2902.5</td>
<td>2979.0</td>
<td>2963.2</td>
<td>3005.4</td>
<td>3027.3</td>
<td>3087.5</td>
<td>3120.0</td>
</tr>
</tbody>
</table>

### Table 3

<table>
<thead>
<tr>
<th>Parameters of PEM fuel cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values</td>
</tr>
<tr>
<td>Cell rated voltage</td>
</tr>
<tr>
<td>Cell exchange area</td>
</tr>
<tr>
<td>Reference temperature</td>
</tr>
<tr>
<td>Exchange current density</td>
</tr>
<tr>
<td>Maximum current density</td>
</tr>
<tr>
<td>Ideal gas constant</td>
</tr>
<tr>
<td>Faraday constant</td>
</tr>
<tr>
<td>Charge transfer coefficient</td>
</tr>
<tr>
<td>Hydrogen gas constant</td>
</tr>
<tr>
<td>Oxygen gas constant</td>
</tr>
<tr>
<td>Volume of anode (cell)</td>
</tr>
<tr>
<td>Volume of cathode (cell)</td>
</tr>
</tbody>
</table>

### Table 4

<table>
<thead>
<tr>
<th>Parameters of the DC/DC converter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values</td>
</tr>
<tr>
<td>( \phi ) (w, P_a)</td>
</tr>
<tr>
<td>5A</td>
</tr>
<tr>
<td>10A</td>
</tr>
<tr>
<td>50A</td>
</tr>
<tr>
<td>100A</td>
</tr>
<tr>
<td>( \geq 150A )</td>
</tr>
</tbody>
</table>

### Table 5

<table>
<thead>
<tr>
<th>Parameters of the vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values</td>
</tr>
<tr>
<td>Vehicle mass</td>
</tr>
<tr>
<td>Density of air</td>
</tr>
<tr>
<td>Coefficient of air resistance</td>
</tr>
<tr>
<td>Windward area of the vehicle</td>
</tr>
<tr>
<td>Rolling resistance coefficient</td>
</tr>
<tr>
<td>Radius of wheels</td>
</tr>
<tr>
<td>Efficiency of the transmission system</td>
</tr>
<tr>
<td>Correction coefficient of the rotation mass</td>
</tr>
</tbody>
</table>

### 2.5. Model of the vehicle

The vehicle parameters are shown in Table 5 which can be used to calculate the power requirement with different road maps. The aggregate demand power needs to overcome the rolling frictional resistance, the component resistance of the vehicle's weight acting on the road with slope \( \theta \), the air resistance, and the acceleration resistance of the vehicle. Therefore the power requirement (power vs time) can be calculated by the following equations:

\[
P_i = \eta (\mu M g \sin \theta + M g \sin \theta + 0.5 C_{air} A_{wind} u^2 + \frac{du}{dt} \delta M) u
\]  

where \( \eta \) denotes the efficiency of the transmission system, \( \mu \) denotes the rolling resistance coefficient, \( M \) denotes the vehicle mass, \( g \) denotes the gravitational acceleration, \( \theta \) denotes the grade of the road, \( C_{air} \) denotes the density of air, \( A_{wind} \) denotes the windward area of the vehicle, \( C_{air} \) denotes the coefficient of air resistance, \( u \) denotes the vehicle speed, \( \delta \) denotes the correction coefficient of the rotation mass.
3. Energy management system

To make the batteries and supercapacitors work together with the fuel cell, the energy management system is required. The lithium-ion batteries and supercapacitors are also responsible for recovering most of the energy when the vehicles brake. In this section, the SOC and power capability prediction methods are first introduced. Then a PID based oxygen excess ratio (OER) control is presented to optimize the fuel cell output net power. Finally, the finite state machine (FSM) based strategy is developed for the lithium-ion battery, supercapacitor, and fuel cell system.

3.1. SOC estimation and power capability prediction

The energy management system and the FSM based energy management strategy mentioned above require accurate SOC and power capability prediction. Therefore the model based SOC estimation and power prediction algorithm are firstly introduced.

3.1.1. SOC estimation

The battery SOC is defined as:

\[ z_{b,k} = z_{b,k-1} - \frac{i_{b,k} \Delta t}{C_N} \]

where \( z_b \) represents the battery SOC, \( i_b \) represents the battery load current, \( \Delta t \) represents the time interval, \( C_N \) is the battery maximum available capacity, and \( \eta \) is the coulombic efficiency.

There are many approaches discussed in literature for the SOC estimation of the lithium-ion battery, among which the model-based approach is an efficient approach. Based on the developed battery model, the discrete time state space equations can be deduced as:

\[
\begin{bmatrix}
V_{p,k+1} \\
Z_{b,k+1}
\end{bmatrix} =
\begin{bmatrix}
\text{e}^{-\Delta t/C} & 0 \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
V_{p,k} \\
Z_{b,k}
\end{bmatrix} + \begin{bmatrix}
(1 - \text{e}^{-\Delta t/C})R_f \\
-\Delta t/C_N
\end{bmatrix} i_{b,k}
\]

\[ V_{b,k} = [1 - \partial V_{soc}/\partial z_{b,k}] V_{p,k} - R_f i_{b,k} \]

(21)

Based on Eq. (21), methods like unscented Kalman filter [5] or extended Kalman filter [6] can be used for system state and parameter prediction.

The voltage behavior of the supercapacitor is more linear than the lithium-ion battery. Therefore, the SOC can be replaced by the state-of-voltage (SoV) for the supercapacitor which can be deduced as follows:

\[ z_{sc,k} = \frac{V_{b,k} - V_{sc,min}}{V_{sc,max} - V_{sc,min}} \]

(22)

where \( V_{b,k} \) represents the terminal voltage of the supercapacitor, \( V_{sc,max} \) and \( V_{sc,min} \) represent the maximum and minimum terminal voltages, respectively.

3.1.2. Power capability prediction

In vehicular energy management, the power prediction for acceleration or braking is required. According to Ref. [6], the power capability of the lithium-ion battery can be defined as:

\[
\begin{align*}
p_{b,ch}^{min} &= \text{max}(P_{b,min}, V_{b,k} + L_{min}) \\
p_{b,ch}^{max} &= \text{min}(P_{b,max}, V_{b,k} + L_{max})
\end{align*}
\]

(23)

where \( P_{b,min} \) and \( P_{b,max} \) represent the minimum charge power and maximum discharge power, \( V_{b,min} \) and \( V_{b,max} \) represent the minimum cut-off power and maximum cut-off power for discharging and charging, \( L_{min} \) represents the battery terminal voltage for a future period \((k+L)\), \( I_{min}^{ch} \) and \( I_{max}^{ch} \) represent the minimum charge current and maximum discharge current, respectively.

The supercapacitors have high power than the batteries, the maximum power capability of the supercapacitor can be calculated as:

\[ P_{sc} = \frac{V_{sc}^2}{4 \times R_{sc}} \]

(24)

where \( P_{sc} \) represents the power capability of the supercapacitor.

3.2. OER control

The OER is one of the crucial indexes of the fuel cell system [32]. Regulating the OER to its optimal workspace is one of the approaches to improve the performance of fuel cells. The OER is formulated by the ratio between the quantity of the input and reaction oxygen flow:

\[ \lambda_{O_2} = \frac{q_{O_2}^{in}}{q_{O_2}^{er}} \]

(25)

where \( \lambda_{O_2} \) represents the OER of the fuel cell, \( q_{O_2}^{in} \) and \( q_{O_2}^{er} \) represent the oxygen input flow and reaction flow, respectively.

The control of OER is crucial to the energy management system. On the one hand, a lower oxygen concentration will cause the oxygen starvation effect, which leads to fuel cell degradation. On the other hand, a high OER can improve the power of the fuel cell stack. However, it also causes excessive power increase of the air compressor, and it will reduce the overall efficiency and output net power. To guarantee maximum net power, the OER must be controlled near its optimal value. The output net powers at different OERs have been collected at each reference load current (from 80A to 140A). The results are shown in Fig. 2.

According to Fig. 2, the optimal OER can be expressed as follows:

\[ \lambda_{O_2}^* = f(i_e) = -1.7 \times 10^{-4} i_e^3 + 0.0006 i_e^2 - 0.072 i_e + 5.2 \]

(26)

To avoid oxygen starvation phenomenon and maximize the system net power. We control the mass flow of the oxygen to track the optimal OER value expressed in Eq. (26) by using an adaptive PID control algorithm.

The block diagram of the controller is shown in Fig. 3, and the control algorithm can be expressed as:
\( e(t) = \hat{\lambda}_2(t) - \hat{\lambda}_0(t) \) \quad (27)

\( u(t) = k_p e(t) + k_i \int e(t) dt + k_d \dot{e}(t) \) \quad (28)

where \( k_p \), \( k_i \), and \( k_d \) are proportion, integration, and differentiation parameters.

To evaluate the effectiveness of the PID algorithm for optimal OER control, experiments and simulation of step response are conducted. The experimental and simulated results of step response using traditional feedforward control and PID control are compared in Fig. 4. From the results, we can see that the performance of PID control is superior to the feedforward control during the sudden current step-down or step-up. During 10 s to 20 s, the overshoots of the feedforward control and PID control are 0.153 and 0.128, respectively. The steady-state errors of the feedforward control and PID control are 0.014 and 0.002. The feedforward control oscillates obviously during the moment of reference OER step change. Moreover, the feedforward control has large steady-state errors than PID control. Therefore optimal OER control can be obtained by the proposed controller.

### 3.3. FSM based energy management strategy

The FSM is a mathematical tool that divides problems into finite states with transitions between them, often triggered by events and conditions. In this work, the FSM approach is employed for energy management strategy development. In order to assign the required power of the lithium-ion battery \( P_b \), the supercapacitor \( P_{sc} \) and the fuel cell system \( P_{fc} \), the demand power of the electrical motor \( P_m \), the demand power of the electrical motor \( P_{m,dm} \), the SOC of the battery and supercapacitor \( z_b \) and \( z_{sc} \), the power of the battery \( P_{b,chg}/P_{b,dchg} \) and the power of the supercapacitor \( P_{sc,chg}/P_{sc,dchg} \) are treated as input variables, and the output variables are the required power of the lithium-ion battery \( P_{b} \), supercapacitor \( P_{sc} \) and fuel cell system \( P_{fc} \). The energy management strategies for a battery/fuel cell system and a battery/supercapacitor/fuel cell system are proposed in this section.

#### 3.3.1. Battery and fuel cell system

For the battery/fuel cell hybrid system, the FSM based energy management strategy is shown in Fig. 5(a). The system working mode can be divided into 9 states. When the fuel cell is ready, the energy management system first determines whether the motor's required power is positive (discharge) or negative (charge). If the required power is negative, the lithium-ion battery needs to absorb the motor's braking energy according to its current SOC. If the SOC of the battery is higher than its upper bound limit, the battery will not continue to charge, the system turns to \( S_1 \). Otherwise, if the motor power is lower than the minimum charge power capability of the battery, the system turns to \( S_2 \), else the system turns to \( S_3 \).
Fig. 5. Diagram of FSM based energy management strategy (a) Battery/fuel cell system. (b) Battery/supercapacitor/fuel cell system.

Fig. 6. Structure of the battery/supercapacitor/fuel cell hybrid vehicle.
In the condition that the required power is positive, the system turns into discharge mode. In this working mode, when the required power is higher than the maximum output power of the fuel cell system $P_{fc,\text{max}}$, the fuel cell system provides its maximum output power and the lithium-ion battery provides the rest according to its remaining capacity and maximum discharge power capability. If the SOC of the battery is lower than its lower threshold $z^*_{\text{b}}$, the system turns to S6, in which the battery is not allowed to discharge and the system will reduce power output. If the SOC of the battery is higher than its lower threshold $z^*_{\text{b}}$, judge $(P_m - P_{fc,\text{max}})$ with the battery maximum discharge power.

Fig. 7. Results of battery/fuel cell system under UDDS driving cycle: (a) Battery lower threshold $z^*_{\text{b}} = 0.2$. (b) Battery lower threshold $z^*_{\text{b}} = 0.3$. (c) Battery lower threshold $z^*_{\text{b}} = 0.4$.
If \((P_m - P_{fc,max}) < P_{b,dchg}\), the system turns to \(S4\), else the system turns to \(S5\). When the required power is lower than the maximum output power of the fuel cell system but the SOC of the battery is lower than its lower threshold \(z^*_b\), the lithium-ion battery provides the required power according to its maximum discharge power capability. If the required power is lower than the maximum discharge power capability, the battery provides all the required power and the system turns to \(S8\). Otherwise, the battery provides its maximum power.
discharge power, and the fuel cell system provides the rest, the system turns to S9.

3.3.2. Battery, supercapacitor and fuel cell system

The FSM based control and management strategy for a battery/supercapacitor/fuel cell hybrid system is shown in Fig. 5(b). Compared with the battery/fuel cell system, the supercapacitor has high specific power capability which can help to solve the problem of insufficient power of the battery. When the system is ready, it first determines whether the system is in discharge mode or charge mode. If the required power is negative, the battery and supercapacitor need to absorb the braking energy according to their SOC. If the SOC of both the battery and supercapacitor are lower than its upper bound limit, the system turns to S5. When the SOC of the battery exceeds its upper bound limit, the battery stops charging and the system turns to S2. When the SOC of the supercapacitor exceeds its upper bound limit, the supercapacitor stops charging and the system turns to S3 or S4. If the motor power is lower than the minimum charge power of the battery, the system turns to S4, else the system turns to S3. When the SOC of both the battery and supercapacitor exceed their upper bound limit, the system turns to S1.

When the required power is positive and higher than the maximum output power of the fuel cell system, the fuel cell system provides its maximum output power. In this case, if the SOC of the battery and supercapacitor are lower than their lower threshold $z^*_b$ and $z^*_sc$, both the battery and supercapacitor are not allowed to discharge, the system turns to S6. If the battery SOC is higher than its lower threshold $z^*_b$ but the SOC of the supercapacitor is lower than its lower threshold $z^*_sc$, the system turns to S7 or S8. If $P_m - P_{fc,max}$ is higher than the battery maximum discharge power, the battery provides its maximum discharge power and the system turns to S7, otherwise the system provides the remaining required power and the system turns to S8. If the SOC of the battery is lower than its lower threshold $z^*_b$ but the SOC of the supercapacitor is higher than its lower threshold $z^*_sc$, the supercapacitor provides the remaining required power and the system turns to S9. If the SOC of both the battery and supercapacitor are higher than their lower threshold, the system turns to S10.

When the required power is positive but lower than the maximum output power of the fuel cell system, the system turns to S11 to S16. In

| Performance of battery/fuel cell and battery/supercapacitor/fuel cell systems. |
|----------------------------------|----------------------------------|----------------|
| Battery + Fuel cell              | Hydrogen consumption (kg)        | $\sigma P_b$ (kW) |
| $z^*_b = 0.2$                    | 7.715                            | 8.434           |
| $z^*_b = 0.3$                    | 7.317                            | 8.390           |
| $z^*_b = 0.4$                    | 8.140                            | 8.326           |
| Battery + Supercapacitor + Fuel cell | Hydrogen consumption (kg)        | $\sigma P_b$ (kW) |
| $z^*_b = 0.2, z^*_sc = 0.2$      | 7.406                            | 5.860           |
| $z^*_b = 0.3, z^*_sc = 0.2$      | 8.136                            | 6.300           |
| $z^*_b = 0.4, z^*_sc = 0.2$      | 8.807                            | 6.511           |

$\sigma P_b$: standard deviation of the power of the lithium-ion batteries.

![Fig. 9. Experimental setup: (a) fuel cell stack test system. (b) Battery and supercapacitor test system. (c) PEM fuel cells. (d) Supercapacitors. (e) Lithium-ion batteries.](image-url)
this situation, if the SOC of the battery and supercapacitor are lower than their lower thresholds, the fuel cell system provides the required power and starts to charge the supercapacitor first, the system turns to S11. When the SOC of the supercapacitor is fully charged, the supercapacitor provides the required power and the system turns to S16. If the SOC of the lithium-ion battery is lower than its lower threshold $z^*_{lb}$ but the SOC of the supercapacitor is higher than its lower threshold $z^*_{sc}$, the supercapacitor provides the required power and the fuel cell system starts to charge the lithium-ion battery, the system turns to S12 or S13 according to the battery charge power capability. If the SOC of the lithium-ion battery is higher than its lower threshold $z^*_{lb}$ but the SOC of the supercapacitor is lower than its lower threshold $z^*_{sc}$, the lithium-ion battery provides the required power and the fuel cell system starts to charge the supercapacitor, the system turns to S14 or S15 according to the battery discharge power capability.

4. Simulation study

In this section, simulation studies are conducted to verify the proposed model and energy management strategy. The system models and management strategy are developed and verified by Matlab/Simulink®, which has the merits of high calculation efficiency and low cost. The model parameters of the energy storage system are identified off-line in the laboratory environment. The structure of the battery/supercapacitor/fuel cell hybrid system is shown in Fig. 6. For the battery/supercapacitor/fuel cell hybrid system, in order to match the vehicle power, the cell number is set to 381 and the theoretical hydrogen consumption is 47.625 g/min. The sizing of the lithium-ion batteries and supercapacitors are using the CPE function method which can be found in Ref. [33]. To evaluate the performance of the fuel economy and dynamic property, the real driving cycle is utilized in the above two topological structures. To avoid excessive drops of SOC, the SOC thresholds $z^*_{lb}$ and $z^*_{sc}$ have been added in the energy management strategy.

4.1. Test of battery/fuel cell system

For the battery/fuel cell system, the battery SOC and the power outputs of the battery and fuel cell system with different settings of the battery lower thresholds are compared in Fig. 7. With regards to the output power, it can be observed that the proposed energy management strategy is able to guarantee the required power during the battery and fuel cell combined working mode, and the fuel cell system almost operates at high-efficiency region with its maximum power output under the proposed energy management strategy. However, when the external demand power exceeds the maximum output power of the fuel cell and the battery SOC is lower than its expected threshold, the required power should be only provided by the fuel cell system. Therefore the hybrid power system cannot provide enough output power. The battery system also supplies insufficient load power and absorbs energy from the vehicle feedback braking. The hydrogen consumptions of the vehicle with $z^*_{lb} = 0.2$, $z^*_{lb} = 0.3$ and $z^*_{lb} = 0.4$ are 7.715 kg, 7.317 kg and 8.140 kg, respectively. It indicates that the vehicle can obtain a relatively lower hydrogen consumption with battery lower SOC setting of 30% under the tested driving cycle.

4.2. Test of battery/supercapacitor/fuel cell system

It is worth noting that there is some drawbacks of the fuel cell system with the battery as its only energy storage device. Although the battery can guarantee the required power of most cycles, it cannot supply and absorb very high energy of acceleration or braking. Moreover, the battery needs to be charged when the SOC is lower than
its limiting threshold. When the battery SOC is lower than its lower threshold and the required power is higher than the maximum output power of the fuel cell system, the system can be only supplied by the fuel cell and reduce power output.

The SOC change and power outputs of the battery/supercapacitor/fuel cell system with different SOC thresholds are compared in Fig. 8. For the battery/supercapacitor/fuel cell system, with regards to the power curves, it can be seen that the proposed energy management strategy is able to guarantee the required power during most of the driving cycles. The supercapacitor helps to generate and absorb the power that either the fuel cell or the lithium-ion battery is not able to generate and absorb.

Compared with the battery/fuel cell system, the supercapacitor with fast response can fulfill the load power demand. In addition, the power fluctuations of the batteries are smaller than the battery/fuel cell system which extends the life of the battery system. Moreover, the SOC of battery and supercapacitor are kept in their defined threshold ranges under the proposed energy management strategy.

The vehicular hydrogen consumption of the battery/fuel cell system and battery/supercapacitor/fuel cell system under the tested driving cycle are compared in Table 7. The hydrogen consumption with $z_b^* = 0.2$ and $z_{sc}^* = 0.2$ is 7.406 kg. With the same lower SOC thresholds of the supercapacitor, the vehicle hydrogen consumptions are 8.136 kg and 8.807 kg at the condition that $z_b^* = 0.3$ and $z_{sc}^* = 0.4$. When the SOC lower threshold of the supercapacitor is constant, the hydrogen consumption of the system increases with the increase of the SOC threshold of the battery. The standard deviation of the lithium-ion batteries’ power is calculated and compared in Table 7. The results indicate that compared with the battery/fuel cell hybrid power sources system, the fluctuations of the power of the lithium-ion batteries are less in the battery/supercapacitor/fuel cell hybrid power sources system.

5. Experimental verifications with the real physical system

To further verify the proposed energy management strategy, the experimental verifications with the real physical system are given in this section. The physical experimental setup is shown in Fig. 9. The fuel cell test system manufactured by Greenlight Innovation and the battery/supercapacitor test system manufactured by Neware Technology Limited. are used to test the battery/supercapacitor/fuel cell hybrid system, which are shown in Fig. 9(a) and (b). The tested PEM fuel cells, supercapacitors, and lithium-ion batteries are shown in Fig. 9(c), (d) and (e).

An ideal PEM fuel cell model is assumed for the simulations in the previous section, to further evaluate the fidelity of the proposed method, experimental verifications with real experimental data are conducted in this section. The polarization curves of the tested fuel cell stack (3 kW/19.5 V) are shown in Fig. 10(a) and (b). From the testing results, we can see that the simulated results of the fuel cell stack model can approximate the polarization behavior of the real PEM fuel cell stack. The conformity of experimental and simulated results illustrates the rationality of the simulation model and its foundational mathematical model.

To verify the proposed energy management strategy with FSM, experiments are conducted under varying load conditions and the SOC.
thresholds $z_{p}^{*}$ and $z_{c}^{*}$ are set to 0.2 in order to prevent over-discharging. The experimental results of the energy management strategy with FSM are shown in Fig. 11. From the figure, we can see that the proposed energy management strategy with the battery/supercapacitor/fuel cell hybrid structure can satisfy most of the load demand, whereas the battery/fuel cell hybrid structure cannot satisfy the load demand when the SOC of the lithium-ion batteries drops to its lower threshold. The fuel economy and fluctuation of the battery system are compared in Table 8. The hydrogen consumptions of the battery/supercapacitor/fuel cell hybrid structure and the battery/fuel cell hybrid structure are 0.583 kg and 0.608 kg. The standard deviations of battery power of the battery/supercapacitor/fuel cell hybrid structure and the battery/fuel cell hybrid structure are 0.461 kW and 0.664 kW. The power fluctuations of the lithium-ion batteries in the battery/supercapacitor/fuel cell hybrid structure are less than that in the battery/fuel cell hybrid structure. This is because the supercapacitors help to share the instantaneous high-power fluctuations. The experimental results are in good agreement with the simulation results in Section 4.

To further verify the proposed energy management strategy with FSM, the PID control method is compared with the proposed FSM in the battery/supercapacitor/fuel cell hybrid structure, and the SOC thresholds of the lithium-ion battery and supercapacitor ($z_{p}^{*}$ and $z_{c}^{*}$) are set to 0.4. The experimental results of the proposed method and PID control method are shown in Fig. 12. The PID control method is used to keep $z_{p}^{*}$ tracking the setting value. From the figure, we can see that the proposed energy management strategy tends to use ultracapacitors rather than batteries compared with the PID control method. The hydrogen consumptions of the proposed energy management strategy and the PID control method are 0.674 kg and 0.679 kg. The results indicate that the energy management strategy with FSM has higher efficiency and can extend the life of the battery.

6. Conclusions

The PEM fuel cells have been considered as one of the effective ways to solve environmental and energy problems. The sole fuel cell system cannot satisfy the dramatical change of motor power demands. Hence, the PEM fuel cells are always combined with other energy storage devices in order to fulfill their power demands and increase the power density of the system. The energy management system is an important part of the vehicular power system. In this work, a finite state machine strategy is proposed for energy management of hybrid energy system. The charge and discharge power capabilities of the battery and supercapacitor have been considered as important parameters in the proposed energy management strategy. Moreover, a PID based EOR control algorithm is presented to maximize the output net power. To evaluate the performance of the fuel economy and dynamic property, the real driving cycle of UDDS is utilized. Both the simulations and experiments with real physical system indicate that the proposed strategy is able to guarantee required power during most of the driving cycles. Compared with the fuel cell system with the battery as its only energy storage device, the battery/supercapacitor/fuel cell system can fulfill the power demand. Moreover, the power fluctuations of both the battery and fuel cell in this hybrid structure are smaller than the battery/fuel cell system which extends the life cycles of the battery and fuel cell system.

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