A Comparative Study of Power Distribution Strategies for Fuel Cell and Supercapacitor Hybrid Power Source System

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Abstract
The power management especially the power distribution strategy of the multi-sources energy system is an important issue. This paper presents a comparative study of power distribution strategies for the fuel cell and supercapacitor hybrid power source system. Two types of power distribution strategies have been put forward and compared systematically. The experiment and simulation results indicate that the fuel economy of different power distribution strategies depends on their driving schedule. However, the presented rule-based power distribution strategy has the potential to reduce energy shocks of the fuel cells and can prolong the lifespan of the fuel cells, which is more suitable for the fuel cell and supercapacitor hybrid power source system.

Keywords: Power distribution strategy, Fuel cell, Supercapacitor, Rule-based control, PID control

1. Introduction
Nowadays fuel cells have attracted much attention because of their high efficiency and environmental friendship. Therefore, many countries rank the fuel cell development as a high priority in their energy policy[1]. The technical developments of the proton exchange membrane fuel cell vehicles have been followed with interest in the area of automobile industry. Compared with the battery powered electric vehicles, fuel cell vehicles have great superiorities in energy efficiency, endurance mileage, charging speed and climate tolerance. The energy conversion efficiency of the fuel cell vehicle is not limited by Carnot cycle, and its energy conversion efficiency can be as high as 60%~70%, which is nearly twice of the ordinary internal combustion engine. The single run mileage for a today's fuel cell vehicle can be more than 700 km, which is not significantly different from a petrol vehicle, but it's twice the range of a battery powered electric vehicle. Moreover, in terms of energy replenishment, the fuel cell vehicle can also be quickly charged through a hydrogen station like a conventional gasoline car. However, it is difficult to reach such a speed for the battery powered electric vehicle, which increases the time cost of long-distance travel imperceptibly. In addition, fuel cell vehicles are much more resistant to cold temperatures than the battery powered electric vehicles. In winter, once the car owner turns on the air conditioner, the mileage will decrease rapidly with naked eyes. However, the fuel cell vehicle generates extra heat as well as electricity from the chemical reaction of hydrogen and oxygen. This heat can be used to give warm wind with no impact on the endurance performance.

To enhance the power response and capability of energy recovery, the fuel cells are always combined with other energy storage systems such as batteries and supercapacitors. The supercapacitor is an electrochemical capacitor used to provide peak power for a short duration, and the electrical characteristic of a supercapacitor is similar to that of a capacitor[2]. In Ref.[3] Wang et al. presented a multi-timescale power and energy evaluation approach for the battery and supercapacitor hybrid system. Compared with the lithium-ion battery, the supercapacitor provides fast and effective energy output because of its high power density and high efficiency[4]. Therefore in many applications, the supercapacitors are integrated with fuel cells as buffers which make this hybrid system more robust.

The power management especially the power distribution strategy of a fuel cell and supercapacitor hybrid system is important. In Ref.[5] Rodatz et al. presented an optimal power management of a fuel cell and supercapacitor powered hybrid vehicle. The goal
of the strategy is to optimize the global hydrogen consumption while maintaining drivability. Thounthong et al. presented an control strategy for a fuel cell and supercapacitor hybrid electric vehicle application, in which the fuel cells are working in steady state and the supercapacitors are working during transient energy delivery or recovery[6]. In Ref.[7] Payman et al. presented a nonlinear control method for a fuel cell and supercapacitor hybrid electrical system, which is safe and efficient. In this paper, a comparative study of power distribution strategies for fuel cell and supercapacitor hybrid power source system is presented. First, the vehicle structure of a fuel cell/supercapacitor hybrid system is presented. Then a rule-based power distribution strategy and a PID control based power distribution strategy have been put forward. The hydrogen consumption and performance of the proposed power distribution strategies have been compared systematically with experiments and simulations. The results indicate that the rule-based power distribution strategy has the potential to reduce energy shocks of the fuel cells so that it can prolong the lifespan of the fuel cells, which is more suitable for the fuel cell and supercapacitor hybrid power source system.

2. Structure of fuel cell/supercapacitor hybrid system

The vehicle structure of a fuel cell/supercapacitor hybrid system is presented as shown in Figure.1. In this structure, the fuel cell and DC/AC inverter are connected by a unidirectional DC/DC converter in order to match the voltage level. The supercapacitor and the DC bus are connected by a bidirectional DC/DC converter in order to provide supplemental power for starting, accelerating and climbing, and recover energy from vehicle braking. The advantage of this presented structure is that the supercapacitor can provide the transient power and recover braking energy so that the burden of the fuel cell system is alleviated, which prolongs the life cycle of the fuel cell system.

3. Methodology

3.1 Rule-based power distribution strategy

In order to rationally assign the demand power of the vehicle motor, the rule-based power distribution strategy is presented as shown in Figure. 2. The demand power of the motor $P_m$ and the State-of-Voltage (SOV) of the supercapacitor are treated as two input variables. The output variables are the required power of the fuel cell system $P_{fc}$ and supercapacitor $P_{sc}$. According to Ref.[8], the SOV for the supercapacitor can be deduced as follows:

$$z_{sc,k} = (V_{c,k} - V_{sc,min})/(V_{sc,max} - V_{sc,min})$$

where $z_{sc,k}$ represents the SOV of the supercapacitor at the $k$th sampling time, $V_{c,k}$ represents the terminal voltage of the supercapacitor at the $k$th sampling time, $V_{sc,max}$ and $V_{sc,min}$ represent the maximum and minimum terminal voltage, respectively.

The maximum power capability of the supercapacitor can be calculated as:

$$P_{sc} = V_c^2/4R_{sc}$$

where $P_{sc}$ represents power capability of the supercapacitor, $V_c$ represents the terminal voltage of the supercapacitor, $R_{sc}$ represents the internal resistance of the supercapacitor.

The rule-based power distribution strategy can be divided into 4 cases: (1) Fuel cell startup. In this case, the fuel cell system needs to be activated by auxiliary power. Therefore all the demand power of the motor will be provided by the supercapacitor. (2) Energy recovery. In the condition that the demand power is negative, the vehicle braking energy is recovered by the supercapacitors due to its SOV. (3) Fuel cell and supercapacitor combined working mode (FC+SC). In the condition that the demand power is positive and the SOV of the supercapacitor is within its upper and lower bounds (20% ≤ SOV ≤ 80%), the fuel cell provides a steady power output $P_{sc}$ and the power of the supercapacitor is the residual of the demand power and the steady power. (4) Fuel cell individual working mode (FC). If the SOV of the supercapacitor is lower than its lower bound or higher than its upper bound, the demand power of the motor will be provided by the fuel cell.

3.2 PID control based power distribution strategy

The PID control is widely used in the industrial process control owing to its simple structure and high efficiency. In order to make the fuel cells and supercapacitors work together and meet the demand power of the motor, a PID control based power distribution strategy is presented as shown in Figure. 3. The principle of this control strategy is to keep the SOV
of the supercapacitor near its enactment value SOV*, so that the system can calculate the required power of the fuel cell system and supercapacitor automatically through the closed loop control algorithm. As shown in Figure 3, the PID controller functions the hydrogen flow valve by the residual of the stated and estimated SOV, which changes the power output of the fuel cell.

![Rule-based power distribution strategy](image1)

**Figure 2** Rule-based power distribution strategy.

![PID control based power distribution strategy](image2)

**Figure 3** PID control based power distribution strategy.

4. Simulation experiment and discussion

To compare the performance of hydrogen consumption and dynamic property of the proposed two power distribution strategies for the fuel cell/supercapacitor hybrid energy system, simulation experiments are designed and introduced in this section. The vehicle model with a fuel cell/supercapacitor hybrid system and the presented two power distribution strategies are developed and verified by Matlab/Simulink. The simulated results of the demand power of the motor, the required power of the fuel cell system and supercapacitor, and SOV of the supercapacitor under different road maps are shown in Figure 4 and Figure 5.

The hydrogen consumptions of the rule-based power distribution strategy and the PID control based power distribution strategy under the urban dynamometer driving schedule (UDDS) are 3.460 kg and 3.290 kg, respectively. For the federal urban driving schedule (FUDS), the hydrogen consumptions of the rule-based power distribution strategy and the PID control based power distribution strategy are 1.637 kg and 1.704 kg, respectively. For the UDDS, the PID control based power distribution strategy has relatively lower hydrogen consumption than the rule-based power distribution strategy. However, in the FUDS, the hydrogen consumption of the rule-based power distribution strategy is lower than the PID control based strategy. The fuel economy of different power
distribution strategies depends on the driving schedule. From the results in both UDDS and FUDS, we can see that with the rule-based power distribution strategy, the fuel cells can provide a steady power while the transient peak power can be provided by the supercapacitors. The supercapacitors can also recover most of the energy when vehicle brakes. Therefore this strategy is more suitable for the fuel cell and supercapacitor hybrid power source system in terms of system stability and durability.

![Figure 4](image1.png)

Figure 4 Results under UDDS: (a) Rule-based power distribution strategy. (b) PID control based power distribution strategy.

![Figure 5](image2.png)

Figure 5 Results under FUDS: (a) Rule-based power distribution strategy. (b) PID control based power distribution strategy.

5. Conclusions

This paper presents a comparative study of two power distribution strategies used for energy management system in the fuel cell and supercapacitor hybrid power source system. First, the vehicle structure of a fuel cell/supercapacitor hybrid system is presented. Then, the rule-based power distribution strategy and the strategy based on PID control have been put forward. Simulation experiments are designed to compare the performance of the proposed two power distribution strategies. The results indicate that the rule-based power distribution strategy has the potential to reduce energy shocks of the fuel cells which can prolong the lifespan of the fuel cells and it is more suitable for the fuel cell and supercapacitor hybrid power source system.

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Reference


