



Article Investigation on Energy Flow Characteristics of Fuel Cell System Based on Real Vehicle Tests

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Abstract: For fuel cell hybrid vehicles, the energy distribution mechanism of the fuel cell and power battery should reasonably allocate the power output of the fuel cell and power battery, optimize the efficiency of both and control the power battery SOC to fluctuate within a reasonable range. To test the energy flow and operation characteristics of the powertrain of two hybrid car models on the market, two test vehicles (called vehicle A and vehicle B in this paper) are tested on an AIP 4WD chassis dynamometer under constant power and the China Light-Duty Vehicle Test Cycle-Passenger cycle condition, respectively. The test results show that vehicle A has a smaller power battery SOC variation interval and a lower variable rate than vehicle B. The cumulative power battery output energy of vehicle B is more significant than that of vehicle A. More importantly, the current rare public test reports of fuel cell vehicles make this study very valuable. This paper has important reference significance for the energy flow characteristics and energy management strategy of existing fuel cell hybrid vehicles.

Keywords: fuel cell; energy management strategy; operating characteristic; energy flow; vehicle test

1. Introduction

With global energy and environmental problems increasingly prominent, the development of new energy vehicles has become the consensus of all countries in the world [1,2]. As significant consumers of oil and carbon dioxide emissions, cars need to undergo revolutionary reforms. Various governments have introduced different policies to support the development of new energy vehicles, and the market for new energy vehicles is now expanding. As a representative of new energy vehicles, fuel cell hybrid vehicles have made significant development.

1.1. Literature Review

Fuel cell hybrid vehicles (FCHVs) operate with the fuel cell as their primary power source and the battery or supercapacitor as their secondary power source. This hybrid power-distribution method has been widely used in FCHVs. As a result, the hybrid powerdistribution model for FCHVs has been the focus of numerous studies. The critical topic for FCHVs in energy management strategies is controlling fuel cell systems and energy storage systems [3,4]. The energy management strategy (EMS) aims to achieve good load sharing between the two energy systems. The energy is fed to the DC bus. Finally, the



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). DC (direct-current) voltage is provided to the inverter to convert the DC voltage to AC (alternating current) voltage so that the AC motor can be controlled [5–8]. Most of the domestic and international research on control strategies for FCHEV energy management systems include proportional–integral–derivative (PID) controllers, operating state-based models, rule-based or fuzzy logic (FL), equivalent consumption minimization strategies (ECMS), predictive model control, and optimization control [9–11].

Several researchers have presented management algorithms based on PI and sliding mode control [12]. The energy management allows the system to operate in three modes depending on the load distribution and the SC charge state. The DC bus voltage, FC, and SC currents track their reference values well under different test conditions. However, the PID control does not constrain the control quantities and is not suitable for handling sudden changes in operating conditions.

Rule-based or fuzzy logic energy management strategies rely on logic rules developed by specialists. The development of such logic rules is highly dependent on the developer's experience and experimental results [13]. Some energy management strategies classify the SOC of a Li-ion battery into high, medium, and low states. The fuel cell operates high-output or off (low output) conditions for different SOC states. However, the statespecific control strategy is generally based on the known operating state of the vehicle, such as whether the car is starting, climbing, accelerating, braking or cruising. The output is determined by combining the operating state and the selected input, including the power required by the load, the state of the battery charge, and the vehicle's operating conditions. Rule-based control strategies are simple in structure, and at the same time, have a degree of practicality [14]. In the energy management of FCHVs, the choice of operating mode depends heavily on the input variables, such as load power, vehicle speed, battery SOC, etc. The control strategy has the advantages of simplicity of structure, robustness, and suitability for real-time applications. Hwang et al. [15] enable the power output of the hybrid system to vary based on different operating conditions, including high power, low power, standard power, and charging modes. The relationship between the dual power output, hydrogen consumption, and lithium-ion battery state of charge was also observed under ECE (Economic Commission of Europe) driving conditions to evaluate the overall efficiency. The results show that the effect of different maximum power levels on the overall efficiency of the Li-ion battery is not significant.

Rule-based fuzzy control is an extension of the deterministic rule-based control strategy [16]. The basic idea of this strategy is to formulate a collection of fuzzy IF-THEN rules from human knowledge and reasoning. Its distinctive features are insensitivity to the system model, robustness, adaptation to dynamic processes, and complex nonlinear time-varying problems. Li et al. [17] used a fuzzy logic control approach to design an EMS for a hybrid vehicle with a fuel cell stack plus a power battery. Erdinc et al. [18] used a wavelet and fuzzy logic-based EMS for hybrid electric vehicles (HEVs). The wavelet transform is responsive to transient changing signals such as HEV power demand. The results show that the battery pack helps the FC to supply the steady-state load demand. The low-frequency part of the braking energy is considered when developing the EMS—the output power of the supercapacitor alternates between positive and negative depending on the charge/discharge. Li et al. [19] presented a fuzzy logic controller-based fuel cell hybrid system based on power management optimization. They simulated the system in three operating conditions: urban dynamometer driving schedule (UDDS), highway fueleconomy test (HWFET), and new European driving cycle (NEDC). The hybrid vehicle loses more energy in all three cycles and is the least efficient in the UDDS cycle. Additionally, there are several more substantial braking phases in the UDDS cycle, so more batteries are needed to collect regenerative energy. In contrast, for the HWFET, the overall efficiency is highest due to near-constant power demand and slight acceleration and deceleration, and the fuel cell outputs more power than the other cycles.

For the energy management of fuel cell hybrids, if the power distribution is pure, then conventional control strategies will do the job well. However, when considering hydrogen fuel consumption, battery replacement, and other operating costs, it is necessary to use an optimal control method based on some optimization algorithm [20–22]. The Equivalent Consumption Minimization Strategy (ECMS) enables global-to-local optimization by minimizing the equivalent fuel consumption [20]. The method aims to achieve optimal control and reduce fuel consumption by reducing the global optimization to an immediate minimization problem. Fares et al. [23] proposed optimizing the FCHV controller based on a weighted, improved dynamic programming technique and a PID controller. A comparison between offline and online simulations shows a good match between the power profile of the power supply and the battery SOC profile. The strategy saves about 15% of the hydrogen consumption compared to the state machine control algorithm. The adaptive monitoring strategy for a fuel cell/battery-driven bus proposed in [24] consists of ECMS, a vehicle auxiliary power-estimation algorithm, battery continuous charging algorithm, and fuel cell performance-identification algorithms. Experimental results show that the strategy reduces fuel consumption from 9.5 kg (100 km) to 9.3 kg (100 km) under typical operating conditions in Chinese city buses. The output power of the fuel cell system decreases at a rate of 0.26 W/km (0.628%) over 8000 km, and the battery SOC is consistently maintained at around 70% in bus routes. Ouddah et al. [25] compared two energy management strategies with another FCHV. The first is a frequency division-based EMS with a frequency decomposition that assigns a frequency component to each energy source. In this strategy, the fuel cell is set to supply the low frequency, and the battery is charged to deliver the high frequency. The other EMS is an optimal control strategy that uses the Pontryagin minimum principle.

Another EMS in FCHEVs is the predictive control strategy. This strategy uses a model that predicts future output based on the amount of state the model already has. Compared to other management strategies, the predictive control strategy can enable the whole vehicle energy flow to achieve the desired results and constrain some control variables [26]. In addition, predictive control has the advantage that it can handle large systems with a large number of variables, as its model is derived from numerical optimization [27].

Compared with the energy management technology of advanced models, hydrogen fuel cell vehicles in China are still relatively backward, mainly in terms of high hydrogen consumption, small volume mass power density, and immature energy management technology of the whole car. Therefore, by benchmarking and learning from the advantages of advanced models, we can quickly improve the quality of domestic fuel cell vehicles. It is understood that the power cell capacity of domestic passenger vehicles is generally above 16 KW·h. In comparison, the power battery capacities of the two test models are 1.56 KW·h and 1.65 KW·h, respectively, which is more than ten times different. It is necessary to study the role of power batteries in other working conditions and optimize the EMS.

1.2. Contributions of This Work

This paper takes two typical FCHVs as test objects to study the fuel cell energy flow and operation characteristics. The power stack power, battery power, battery SOC, and vehicle speed of both vehicles under constant power conditions and China light-duty vehicle test cycle-passenger (CLTC-P) cycle conditions are tested, respectively. In this paper, the test objects are called vehicle A and vehicle B, respectively. It was found that the vehicles' fuel cell and battery energy management strategies are mainly developed based on power, followed by comparing the energy flow and operation characteristics of the dynamical system.

1.3. Organization of the Paper

The remainder of this paper is structured as follows: Section 2 provides a brief introduction to the research object. Section 3 presents the detailed test stand and method. Section 4 details test results and discussion, and Section 5 concludes.

2. Research Object

2.1. Introduction to the Power Systems

The power system of test vehicle A uses fuel cells as the core. There is no conventional fuel cell engine and no transmission, and inside the cabin is the control unit for the electric motor. The fuel cell stack arranged under the vehicle is the core of the whole system.

Like vehicle A, vehicle B uses a combination of fuel-cell and battery power and is an electric hybrid. Vehicle A integrates the powertrain of the fuel cell engine and the power electric drive system, which is the system's core component. The high-voltage battery is placed at the rear of the car to preheat the vehicle and recover energy. Vehicle B uses a hydrogen storage system consisting of three identical-sized hydrogen storage tanks, with a storage capacity of 156 L, through innovative design. Figure 1 shows the overall configuration of the powertrain of the two models.



Figure 1. Overall configuration of the vehicles.

2.2. Power Battery Layout Types and Parameters of the Vehicles

Figure 2 shows the battery packs of the vehicles. The layout, types, and parameters of the power batteries of the two models are shown in Table 1.



Figure 2. Two power battery packs: (a) Vehicle A; (b) Vehicle B.

Table 1. Layout, types, and parameters of the studied power battery packs.

Vehicle Type	Vehicle A	Vehicle B
Power Battery	NI-MH	Lithium
Self-discharge Rate	20%	5%
Cycle life	>500	>800
Capacity (kWh)	1.6	1.56
Operating temperature (°C)	$-20 \sim 60$	$-20 \sim 70$
Nominal Voltage (V)	245	240
Decorate Position	Luggage Room	Luggage Room
Cooling Mode	Air Cooling	Hydrocooling

3. Test Method

3.1. Test Stand

The test experiments for both vehicles were conducted in the same environment. The test rig was unified using AIP's 4WD chassis dynamometer, and a complete cycle of tests was performed continuously. The diagram of the test equipment and interface is shown in Figure 3.



Figure 3. Diagram of the test equipment and interface.

3.2. CLTC-P Working Condition

The CLTC-P test condition is the passenger car part of CATC (China Automotive Test Cycle). Compared with NEDC, CLTC removes the element of super high-speed driving, which does not match the actual working condition, and redivides the traffic into three speed intervals, corresponding to low speed, medium speed, and high speed. CLTC reflects more realistic working conditions with Chinese characteristics, including a more reasonable definition of average speed and maximum speed, broader driving conditions, a more reasonable proportion of stopping modes, and more dynamic acceleration and deceleration conditions. CLTC-P includes three speed intervals: low speed (Part 1), medium speed (Part 2), and high speed (Part 3), with a total working time of 1800 s. The working curves are indicated in Figure 4, and the statistical characteristics of the operating curves are shown in Table 2.

3.3. Test Methods and Procedures

The energy flow tests of the two hybrid vehicles were carried out under steady-state power and CTPC cycle conditions, respectively. The test process is shown in Figure 5. See Sections 3.3.1 and 3.3.2 for the specific steps of the test under the two working conditions.



Figure 4. CLTC-P working condition curve.

Features	Overall	Part 1	Part 2	Part 3
Running time/s	1800	674	693	433
Mileage/km	14.48	2.45	5.91	6.12
Maximum speed/(km/h)	114.00	48.10	71.20	144.00
Maximum acceleration/ (m/s^2)	1.47	1.47	1.44	1.06
Maximum deceleration $/(m/s^2)$	-1.47	-1.42	-1.47	-1.46
Average speed/(km/h)	28.96	13.09	30.68	50.90
Average acceleration/ (m/s^2)	0.45	0.42	0.46	0.46
Average deceleration $/(m/s^2)$	-0.49	-0.45	-0.50	-0.54
Acceleration ratio/%	28.78	22.55	30.45	35.80
Deceleration ratio/%	26.44	21.51	28.43	30.95
Uniformity ratio/%	22.67	20.77	21.36	27.71
Idle speed ratio/%	22.11	35.16	19.77	5.54

Table 2. The statistical characteristics of CLTC-P working conditions.



Figure 5. The test flowchart.

3.3.1. Steady-State Power Test

The steady-state power test points were selected regarding GB/T 24554-2009 Fuel Engine Performance Test Methods. When the power output of the fuel cell stack is stabilized at each power point, the accelerator pedal opening is maintained at a constant. A total of eight power points were designed, namely 10 KW, 20 KW, 30 KW, 40 KW, 50 KW, 60 KW, 70 KW, 80 KW, where the chassis dynamometer controlled the vehicle speed to 50 Km/h for the power stack between 10~50 KW, and 80 Km/h for the power stack between 60~80 KW. The output power of the power battery, output power of the fuel cell stack, and vehicle speed were recorded during the test.

The specific test steps for steady-state power are as follows:

- (a) Mount the vehicle on the drum stand;
- (b) Pull up the vehicle speed to 60 kM/h, warm up the machine for half an hour and observe the stable water temperature at the outlet of the electric pile (fluctuation \pm 0.5 °C);
- (c) Stop the vehicle, switch the chassis dynamometer to constant speed mode within 3 s, and adjust the cooling fan airflow to the maximum;
- (d) Pull the speed up to 80 kM/h through the chassis dynamometer;
- (e) Depress the pedal, observe the fuel cell stack output power, stabilize it in the set power ± 0.5 kW range, start timing for 5 min after the timing is finished, switch to the following working condition, and continue the test until the test is completed;
- (f) Observe the fuel cell stack outlet water temperature during the test. After the fuel cell stack outlet temperature is significantly higher than 80 °C, the fuel cell stack power should be immediately reduced to 10 kW working condition for cooling until the fuel cell stack outlet water temperature drops to 60 °C, then continue to complete the test.

3.3.2. CLTC-P Working Condition Test

Both vehicles were subjected to six CLTC-P cycle working condition tests with the following test procedures:

- (a) After the vehicle is fixed to the chassis dynamometer, dip the vehicle for 30 min;
- (b) Warm-up the vehicle, operate the vehicle under a completed CLTC-P cycle, shut down the vehicle when the cycle ends, preset the vehicle;
- (c) Start recording the whole vehicle CAN signal, acquisition frequency 10 Hz;
- (d) According to the CLTC-P working condition table, carry out a continuous cycle working condition test. The hydrogen consumption, chassis dynamometer driving mileage, and other parameters of each process are recorded;
- (e) Stop after completing six cycles of testing;
- (f) Stop data recording and analyze the data.

4. Test Results and Discussion

4.1. Energy Flow Distribution Characteristics of Fuel Cell Stack and Power Cell under Different Modes

4.1.1. Constant Power Mode

In Figure 6, the fuel cell stack is at a low power of 10 kW. When it reached relative stability, the power battery did not output energy significantly and remained at 0 or below. At the maximum test power of 80 KW, the power battery also does not produce energy, and the stack and power battery is kept at a relatively stable stage. This further verifies that the two vehicles' energy management is based on logic-based power following type control strategy rather than the high- and low-power battery SOC thresholds.



Figure 6. Vehicle speed, fuel cell stack power, and power battery power in constant power mode: (a) Vehicle A; (b) Vehicle B.

The two models also show the difference in the constant power operation mode. Figure 7 shows the change in power battery output power after the power of the stack increases from 30 kW to 40 kW. Figure 7 shows that the constant speed and constant power operation of vehicle A are similar to the CLTC-P cycle condition. When the accelerator pedal opening is adjusted from low to high and kept stable, the power of vehicle A's power battery remains around 0. When the accelerator pedal is adjusted from low to high and kept constant, the capacity of vehicle B's power battery slowly decreases from 2.6 kW to 0.5 kW. The above differences also show the relatively greater involvement of vehicle B's power battery than that of vehicle A.



Figure 7. The change of battery output power after the reactor's power rises from 30 kW to 40 kW: (a) Vehicle A; (b) Vehicle B.

4.1.2. CLTC-P Cycle Conditions

At each cycle operating condition, the paper summarizes the calculation of each energy flow within the two models, as detailed in Tables 3 and 4.

Cycle Number	Battery Cumulative Energy Output (kW·h)	Battery Energy Change (kW·h)	Fuel Cell Energy Output (kW∙h)	Total Energy Output (kW∙h)	Battery Energy Output Ratio
1	0.66	0.0225	2.92	2.9425	0.65
2	0.66	0	2.89	2.89	0.66
3	0.66	-0.0075	2.85	2.8425	0.66
4	0.68	0	2.70	2.7	0.68
5	0.70	0.0075	2.76	2.7675	0.7
6	0.70	-0.0075	2.73	2.7225	0.7
Total	4.06	0.015	16.85	16.865	4.1

Table 3.	. The energy	output of	vehicle A
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Table 4. The energy output of vehicle B.

Cycle Number	Battery Cumulative Energy Output (kW·h)	Battery Energy Change (kW·h)	Fuel Cell Energy Output (kW∙h)	Total Energy Output (kW∙h)	Battery Energy Output Ratio
1	1.42	-0.0312	2.31	2.2788	0.64
2	1.34	0.039	2.36	2.399	0.54
3	1.31	0.039	2.47	2.509	0.51
4	1.30	-0.0624	2.4	2.3376	0.58
5	1.31	-0.078	2.17	2.092	0.66
6	1.22	0.0234	2.26	2.2834	0.52
Total	7.9	-0.0702	13.97	13.8998	3.46

4.2. Fuel Cell Stack Operating Characteristics Based on SOC Change Rate

4.2.1. Operating Characteristics of the Two Vehicles

According to the operating characteristics of vehicle B under six consecutive CLTC-P conditions, analysis was carried out on battery SOC and vehicle speed, detailed in the following figure. Figure 8 shows that the battery SOC follows the vehicle speed in a small range, and in each cycle, SOC follows the same vehicle speed trend. In the coming part of the working condition (high speed and rapid acceleration), SOC decreases relatively further. However, overall SOC remains between 69% and 91%, with an average value of 83.3%, as shown in the table below.



Figure 8. Operating characteristics of vehicle B vehicles under six continuous CLTC-P conditions.

According to the operating characteristics of vehicle A under six consecutive CLTC-P conditions, the battery SOC and vehicle speed are analyzed, respectively, as shown in Figure 9. The battery SOC follows the vehicle speed in a small range, and the trend of SOC following the vehicle speed is the same for each cycle. In the latter part of the working condition, i.e., high speed and rapid acceleration phase, the SOC decreases relatively



further, and there are two troughs. However, overall, the SOC remains between 53.5% and 60%, with an average value of 56.7%, as shown in the table below.

Figure 9. Operating characteristics of vehicle A under six continuous CLTC-P conditions.

4.2.2. Comparisons in the SOC Change Rates between the Two Vehicles

The SOC values of both models remain within a specific range during each cycle. The values do not change significantly with the change of vehicle speed and time. The lower and upper limits of the SOC values do not appear regularly. The SOC values remain relatively stable, indicating that the power battery is not continuously discharged and continuously charged. Based on the principle of energy conservation, it can be reflected that the power of the fuel cell stack follows the power change of the drive motor, which means that the EMSs of both models is based on the ability to track the control strategy.

However, as can be seen from Tables 5 and 6, the difference between the maximum and minimum SOC of vehicle A's power battery is smaller than that of vehicle B's battery in each CLTC cycle. The difference between the two models is that vehicle A has a smaller SOC variation interval and lower variation rate than vehicle B. It can be inferred that vehicle A is less dependent on the power battery to drive the vehicle than vehicle B, relying mainly on the electric stack to follow the variation of the drive motor power. The analysis of the internal energy flow of the two models in Section 4.1 also verifies this inference.

Cycle Number	SOC Maximum (%)	SOC Minimum (%)	Range (%)	Average SOC (%)
1	89.5	73.5	16	84.8
2	89.5	76.5	13	85.5
3	90	77.5	12.5	85.7
4	91	72.5	18.5	86.8
5	85.5	69	16.5	81.4
6	80.5	70	10.5	75.7

Table 5. Power battery SOC of vehicle B under 6 consecutive CLTC-P conditions.

Table 6. Power battery SOC of vehicle A under six consecutive CLTC-P conditions.

Cycle Number	SOC Maximum (%)	SOC Minimum (%)	Range (%)	Average SOC (%)
1	59.5	53	6.5	56.1
2	60	53.5	6.5	56.9
3	60	53.5	6.5	56.9
4	58.5	53.5	5	56.5
5	59.5	53.5	6	56.8
6	60	53.5	6.5	57

4.3. Operating Characteristics of the Fuel Cell Stack during the Startup Phase

The power battery intervenes when the vehicle is ready to start from a standstill, and the accelerator pedal is depressed. Figure 10 shows the relationship between the depth of the accelerator pedal and the stack output current for vehicle A. The state of the accelerator pedal represents the drive motor demand torque.



Figure 10. The output power of fuel cell stack in starting phase vs. accelerator pedal depth.

As shown in Figure 10, the first three accelerator pedal signal values are 7%, 10%, and 13%, respectively. However, the fuel cell does not output current when the accelerator pedal is depressed and stabilizes the first three times. The fourth time the accelerator pedal signal value is 16.5%, the stack system starts and stabilizes the current output, and the SOC of the power battery can be measured to be 80%. The fuel cell stack begins when the vehicle's power requirement or power battery SOC is below a minimum threshold. Since the SOC of the power battery here is 80%, which is not below the minimum limit value, the fuel cell stack is starting because the vehicle has power requirements. Here, the power requirement of the vehicle is reflected in pedal depth. When the accelerator pedal signal value exceeds 16.5%, the motor starts and follows the drive motor power. When the accelerator pedal signal value is less than 16.5%, due to the low demand power, to avoid the motor working at high potential, the energy required for the drive motor is entirely provided by the power battery.

Further analysis of the data above shows that between 560 and 600 s, the accelerator pedal value is above 20%, and the stack starts to output current. During the period from 460 to 510 s, the accelerator pedal was maintained at 13%–16%. The stack system did not begin until 520 s when the accelerator pedal signal value was more significant than 16.5%, at which time the power stack started and began to output energy. The power battery SOC is 72.5% (not reaching the low limit for triggering the power stack to start). Therefore, there is every reason to think that the accelerator pedal or motor demand torque is under the trigger condition, which triggers the reactor. During 520–560 s, the accelerator pedal opening is maintained at 15.5–16.5%, and the reactor system is always in working condition, and the output current is kept in a stable state.

In the above data, excluding when the accelerator pedal is at less than 16.5%, the output current of the stack and its trend of change maintain the characteristics of following the motor energy required when the accelerator pedal remains relatively stable, and changes significantly in the middle and rear sections.

5. Conclusions

To study the energy flow and operating characteristics of fuel cell systems, this work tested and compared the fuel cell stack power, power battery power, power battery SOC, and vehicle speed using two typical fuel cell hybrid vehicles as the tested objects. Based on the test results, the following conclusions can be drawn:

- (1) The test vehicles' energy management strategies are developed mainly based on power following. In each CLTC-P cycle, the ratio of cumulative power battery output energy of vehicle B is larger than that of vehicle A, reflecting the relatively higher contribution and participation of power battery in driving vehicle B;
- (2) Vehicle A has a smaller battery SOC variation interval and a lower variable rate than vehicle B. Therefore, compared to vehicle B, vehicle A is less dependent on the power battery when driving the vehicle and relies mainly on the fuel cell stack to follow the variation in the drive motor power;
- (3) In the low-torque demand phase, the reactor does not follow the drive motor power and is driven entirely by the power battery. This strategy can better protect the reactor from the high potential operation. The reactor shows good followability in the medium-to-high torque stabilization phase and the sizeable variable load phase.

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