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Hierarchical control of vehicular fuel cell / battery hybrid powertrain

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Abstract

In a proton exchange membrane (PEM) fuel cell/battery hybrid vehicle, a fuel cell system fulfills the stationary power demand, and a traction battery provides the accelerating power and recycles braking energy. The entire system is coordinated by a distributed control system, incorporating three key strategies: 1) vehicle control, 2) fuel cell control and 3) battery management. They make up a hierarchical control system. This paper introduces a hierarchical control strategy for a fuel cell / battery hybrid powertrain applied in a city bus. The vehicle control strategy comprises three parts: an energy management strategy, a brake regeneration strategy and an active tolerant control strategy. The entire powertrain power is split between the fuel cell system and the battery in such a way that the fuel cell system works in a quasi-steady state and the battery can keep charge sustaining. The braking energy is recycled on the basis of the pedal position and the rotational speed of the electric motor. An active tolerance control strategy is developed to guarantee the work of the entire system in case of malfunctions. A fuel cell system consists of a water and heat management system, an air system, a humidifier system and a hydrogen in-out let system. Control strategies are designed to regulate air supply and water cooling temperature. Primary tasks of a battery management system are to estimate the state of charge (SOC), and to keep the temperature in safety range. A real-time applicable strategy for SOC is developed. The temperature of the battery is controlled by some air fans with on-off strategy. The hierarchical control system was applied on a fuel cell city bus. Experimental results show the effectiveness of the proposed strategy.

Keywords: Fuel cell hybrid system, energy management, brake regeneration, fuel cell control, battery management

1. Introduction

In order to avoid climate change and to reduce dependency on fossil fuels as the predominant primary energy source, novel energy technologies are strongly required in automotive industry. Fuel cell vehicles are set to play a prominent role in traffic applications by offering a more energy efficient and less polluting drive-train alternative to conventional internal combustion engine (ICE) vehicles. They are regarded as one possible ultimate vehicle type for the future human society. Most of the transnational automobile manufacturers have been working on the development of fuel cell system technology since

1990s', and get some achievements in the commercial hydrogen FCVs. GM introduced the Voltec, or noted as E-Flex, in the North American International Auto Show of 2007 [1] as an attempt to standardize future electrically-propelled vehicles, and to allow multiple interchangeable electricity - generating systems [2]. Different fuel cell vehicles can be developed on the basis of Voltec drivetrain. Till now, GM surpassed a million miles of testing with its Chevrolet Equinox FCVs. Daimlaer unveiled the Mercedes Benz B-class Fuel Cell FCV with a 40% smaller stack, providing 30% more power and consuming nearly 20% less hydrogen than the earlier A-class version [3]. Toyota has been working on the development of fuel cell system technology since 1992. Recently, it announced the results of a collaborative fuel cell hybrid vehicle range and fuel economy field evaluation. The Toyota highlander fuel cell hybrid vehicle – advanced (FCHV-adv) achieved an estimated range of 431miles on a single full tank of compressed hydrogen gas, and an average fuel economy of 68.3mile/kg during a day-long trip down the southern California coast [4]. The Volkswagen Passat Lingyu FCVs were built in the summer of 2008 to be presented at the 2008 Beijing Olympic Games. It has a range of 146 miles and can accelerate up to 90mph. It is the result of collaboration among Shanghai VW Automotive Company, Tongji University and the Shanghai Fuel Cell Vehicle Powertrain Company [5]. Similar to this, as results of collaboration among Tsinghua University, Beijing SinoHytec Company, Foton Automotive Company and SAIC motor, several fuel cell city buses are developed for Beijing Olympic Games and Shanghai EXPO. It has a range of 300km and can speed up to 80kmph [6].

In a PEM fuel cell stack, chemical energy in hydrogen is converted into electric energy by electrochemical reactions. Because of the properties of a PEM, output current of a fuel cell stack could not change drastically. Otherwise, performance of the fuel cell stack will decay. Thus, it is necessary to install a traction battery in the vehicular powertrain as the secondary power sources. The application of a traction battery brings two advantages. Firstly the fuel cell can only fulfill the stationary power requirement. Secondly the battery can recycle part of the braking energy from the electric machine.

A hybrid powertrain configuration brings about several control problems. 1) How to coordinate the work of a fuel cell system, a battery and an electric motor? 2) How to control a fuel cell system, e.g. the air control system and the heat management system, so as to fulfill load requirements? 3) How to manage a battery system, e.g. to estimate the SOC (state of charge) so as to avoid over discharging and over charging? Answers to these three questions correspond to three key technologies, 1) vehicle control, 2) fuel cell control and 3) battery management. They make up a hierarchical control strategy.

There are numbers of papers discussing the problems referred above. Prof. Peng Hui et al. introduced global optimization algorithms using dynamic programming or stochastic programming methods for a determined cycle or undetermined cycle, respectively. The fuel consumption can be reduced by 15% to the highest degree in ICE-based hybrid vehicles [7]. Dr. Paganelli et al. introduced the concept of equivalent fuel consumption, which is the fundamental in developing a optimized energy managment strategy [8]. Dr. J.T. Pukrushpan et al. studied modelling and control for PEM fuel cell stack systems, and published several papers. They proposed a nonlinear dynamic model to describe the PEM fuel cell system, and designed feedback controllers basing on the model. Because of the long time constant, the temperature was regarded as a parameter but not a state variable [9]. Prof. Gregory L. Plett published three papers to introduce the application of extended kalman filtering (EKF) in battery management systems. The EKF method isn't only used in estimating state of charge (SOC), but also state of health (SOH) and can determine which cell must be equalized [10-12].

This paper proposes the hierarchical control strategy of the fuel cell / battery hybrid powertrain. It is organized as follows. Section 2 describes the structure of the hybrid system and the hierarchical control system. Section 3 introduces the hierarchical control strategy, including vehicle control strategy, fuel cell control and battery management strategy. Section 4 gives some on-road experimental results. Section 5 is the conclusions.

2. System description

2.1 The hybrid powertrain

Fig. 1 illustrates the structure of the hybrid powertrain applied in a city bus. Two fuel cell systems and Li-ion battery packages are the power sources. Output power of the fuel cell stack is regulated by dc (direct current) to dc converters.

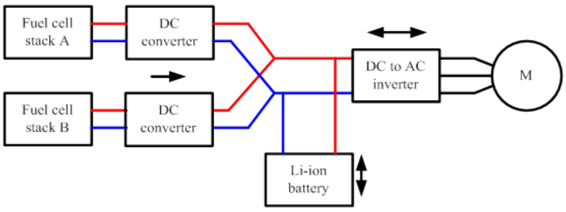


Figure 1: Structure of the PEM fuel cell / Li-ion battery powertrain for a city bus. Lines with arrow(s) show the direction of energy flow.

The Li-ion traction battery is connected to an electric motor directly, so that it can provide the dynamic power in accelerating and recover braking energy during decelerating with very quick response.

2.2 The hierarchical control system

The components of the hybrid powertrain distribute in different places in the city bus. A controller area network (CAN) based distributed system is necessary to coordinate the work of the entire system. Fig. 2 describes the hierarchical structure of the control system with four layers.
The top layer is the driver interface, including an accelerating pedal, a braking pedal, a shift knob and a dashboard. The driver receives information about the vehicle and the status of each component from the dashboard, manipulates the pedals and the shift knob, and controls the vehicle.
The second is the vehicle control layer, incorporating a time triggered controller area network (TTCAN, noted as CAN A in Fig. 2). The vehicle control unit (VCU) receives pedal positions and shift signals, and communicates with other controller nodes. It calculates the vehicle power requirement, estimates the auxiliary

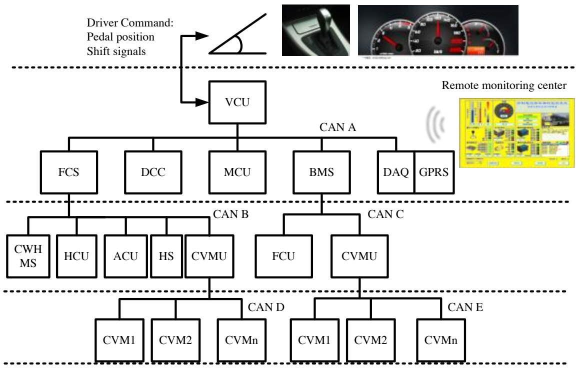


Figure 2: Networked hierarchical control system. VCU-vehicle control unit, FCS-fuel cell management system, DCC-dc/dc converter controller, MCU-motor controller unit, BMS-battery management system, DAQ-data acquisition unit, CWHMS-cooling water and heat management system, HCU- hydrogen control unit, ACU- air control unit, HS- humidifying system, CVMU- cell voltage monitoring unit, FCU-fan control unit

power consumption, and splits the demand power between the two fuel cell stacks and the battery packages.
The TTCAN system involves the fuel cell control system (FCS), dc/dc converter controller (DCC), motor controller unit (MCU), battery management system (BMS) and data acquisition unit (DAQ). The DAQ records the primary status data, and communicates with the remote monitoring center by GPRS modular. In this method, we can monitor the operation of the fuel cell city buses in the office.
The third layer is the subsystem control layer for the fuel cell stacks and the battery package. CAN B and CAN C are defined for the fuel cell system and the battery, respectively. For the fuel cell system, the cooling water temperature, the hydrogen pressure, the air flow and the humidification are controlled so as to keep the fuel cell stack in a suitable status. For the battery package, the highest temperature among all the chips is restricted in safety range by regulating the fans.
The fourth is the chip voltage monitoring layer. The chip voltages are cruising inspected, both for the fuel cell system and the battery packages. Besides, the inner temperatures of several battery chips are measured.

3. Control strategies

Fig. 3 describes the relationship between different control algorithms corresponding to the hierarchical control structure in Fig. 2.
The vehicle control strategy mainly covers three aspects: an energy management strategy, a brake regeneration strategy and an active tolerant control strategy. A supervisory logic is designed to coordinate the three. The fuel cell control strategy and the battery management strategy are regarded as the basis of the vehicle control strategy. As referred in Section 2.2, the three subsystems communicate with each other through TTCAN.

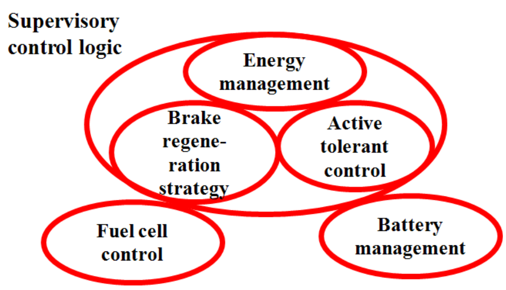


Figure 3: hierarchical structure of control algorithms.

3.1 Vehicle control strategy

3.1.1 Energy management

In a PEM fuel cell / battery hybrid vehicle, the PEM fuel cell system provides the stationary power requirement, and the battery fulfills the accelerating power and recycles brake energy. The target power of PEM fuel cell P_{fctg} include three parts, the average power requirement of the electric motor P_{mavg}, the compensation power for battery charge sustaining P_{comp}, and the vehicle auxiliary power P_{aux}.

$$P_{\mathrm{fcavg}} = P_{\mathrm{aux}} + P_{\mathrm{comp}} + P_{\mathrm{mavg}} \quad (1)$$

The average power requirement of the electric motor is the low frequent component of the power consumption, which can be calculated as follows.

$$P_{\mathrm{mavg}} = \frac{P_{\mathrm{m}}}{\tau \mathrm{s}+1} \quad (2)$$

where P_{m} is the electric power consumption of the motor, τ is a variable time constant. Actually, Equation (2) is a simplified form of power prediction algorithm. In future, the average power requirement should be predicted basing on traffic information, e.g. road conditions, GPS signals [13].

The compensation power for battery charge sustaining is a function of battery SOC. It can be noted as [14]

$$P_{\mathrm{comp}} = k\left(\mathrm{SOC}\text{-}\mathrm{SOC}_{\mathrm{tg}}\right) \quad (3)$$

where k is a coefficient, and $\mathrm{SOC}_{\mathrm{tg}}$ is the target SOC that we want the battery to be kept around.

Vehicle auxiliary power is the power consumed by air conditions and electric power steering systems etc.. It can be estimated basing on the signals of bus voltage, electric motor current, battery current and dc converter current [15].

3.1.2 Brake regeneration strategy

Generally speaking, there are two brake regeneration strategies, parallel strategies and serial strategies [16]. In the former strategy, the electric brake force is added to the friction brake force directly. The energy that can be recycled is limited, but the traditional friction brake system is not disturbed. In the latter, both of the friction force and the electric force are regulated. The recycled energy should be more than that of the former one, but the traditional system is disturbed and maybe it will cause safety problems. The strategy discussed here belongs to the former one. The target torque of the electric motor in decelerating process T_{tg} can be written as

$$T_{\mathrm{tq}} = T_{\mathrm{brk}}\left(n\right)\gamma\left(\beta\right) \quad (4)$$

where T_{brk} is the maximal brake torque of an electric motor. It is a function of the rotational speed n. γ is the brake pedal coefficient. It is a function of the brake pedal position β.

Fig. 4 (a) and (b) illustrate the relationship between T_{brk} and n, and γ and β, respectively.

As described in Fig. 4 (a), idle state control of an electric motor is still an unsolved problem. In order to avoid the unstable area, the maximal torque is zero when the rotational speed is small. After the speed exceeds a certain value, the torque increases linearly to the maximal value. Then it keeps at that level in a speed range. After that, the torque reduces along with the speed, but the power is kept constant. In the last stage, the torque decrease to zero.

As shown in Fig. 4 (b), in order to avoid signal noise and keep safety, the coefficient is zero when the brake pedal position is very small and very large. In the middle of the curve, the coefficient keeps constant.

3.1.3 Active tolerant control

The active tolerant control strategy is designed to guarantee the normal work of the entire system in case of malfunctions, as shown in Fig. 5 [17].

The system consists of two parts: a fault detecting and diagnosis strategy and a reconfigurable algorithm. Critical variables, e.g. the PEM fuel cell temperature, the battery SOC, the battery temperature, the cell voltages of fuel cell and

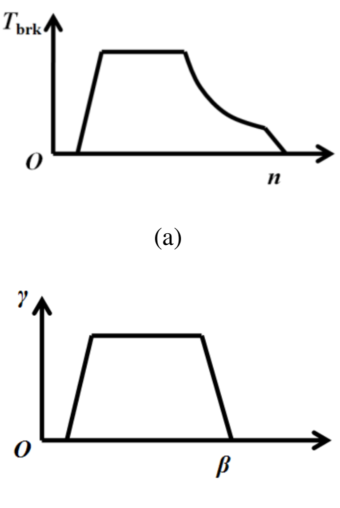


Figure 4: Relationship between (a) maximal brake torque and rotational speed, (b) brake position coefficient and brake position

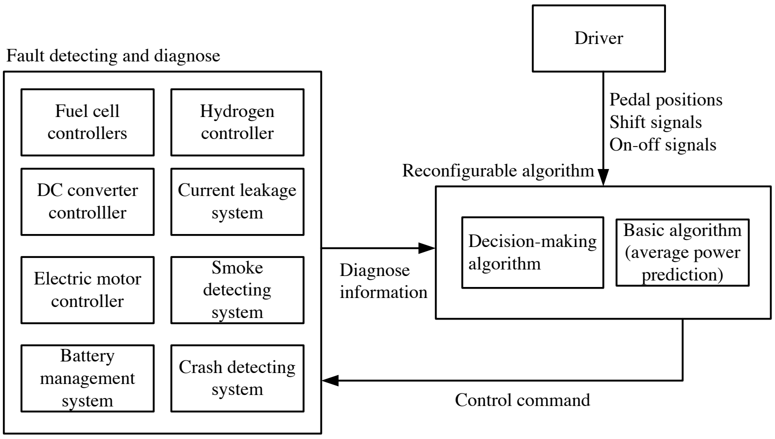


Figure 5: Structure of the active tolerant control strategy [17]

battery, the hydrogen leakage, are monitored and diagnosed in the fault detecting and diagnosis algorithm. The results are sent to the decision-making algorithm. In the decision-making algorithm, several kinds of decisions are made in accordance with the diagnose information given by the fuel cell controllers, the hydrogen controller, the dc converter controller, the current leakage system, the motor controller, the smoke detecting system, the battery management system and the crash detecting system. The reconfigurable algorithm then modifies the results given by the vehicle control algorithm so as to keep the system work normally even if malfunctions.

3.2 Fuel cell control

Fig. 6 illustrates the fuel cell control system. It consists of a hydrogen supply system, a water and heat management system, an air supply system [18].

The compressed hydrogen is stored in several tanks, where the pressure may reach 30Mpa. In order to guarantee safety, the hydrogen pressure is lowered and kept at a stable level using several valves before the hydrogen goes into the stack. Water accumulates in the stack because of the electro-chemical reaction during the operation of the fuel cell, which leading to performance decay. An outlet valve is installed so that the accumulated water can be blown away with hydrogen. The outlet valve, the hydrogen valves for lowing and stabling the pressure are controlled by the HCU.

The electro-chemical reaction generates heat, and causes the temperature to increase. The water and heat management system targets to control the stack temperature in a suitable range using deionized water in a water tank. The water flow is controlled by a water pump. The water goes into the stack with a low temperature, and comes out of the stack with a high temperature. The warm water is then cooled down by a radiator. The water pump and radiator are regulated by CWHSM. The cooling water temperature is measured, and controlled by a feedback control algorithm.

The air supply system is composed of an air filter, a compressor and a humidifier. The impurities in

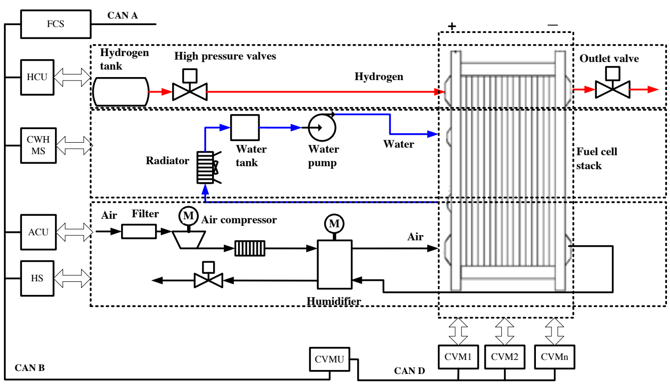
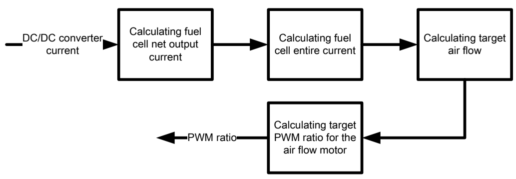


Figure 6: The fuel cell control system [18]

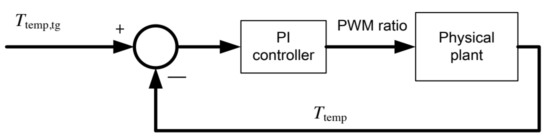
air will cause the catalyst to be poised [19]. Therefore, the air should be filtered before getting into the stack. The air flow is controlled by the compressor with a feed forward + feedback algorithm. There should be some water in the PEM, so that the PEM can conduct protons. Thus, the air needs to be humidified. In the humidifier, the dry air is humidified with the damp-heat air out of the stack. The air compressor and the humidifier are controlled by the ACU and the HS.
A 40kW fuel cell system consists of hundreds of cells. The dynamic processes of cell voltages contain information about the fuel cell stack. It is necessary to measure the voltages for control diagnosis targets. Because of the huge number of cells, the cells are grouped, and the voltages are cruising inspected by CVMs. The network CAN D is designed for the voltage cruising inspecting system. On the basis of the information provided by CVMs, the CVMU extracts the diagnosis information, and communicates with other nodes in the fuel cell control system.
Fig. 7 (a-b) illustrate the control strategy. Because the fuel cell system is a kind of passive power sources, the response of the inner subsystem is always later than the load. Therefore, we use a feed-forward algorithm for the air supply system, as in Fig. 7 (a). The cooling water temperature is controlled by a PI feedback algorithm, as in Fig. 7 (b).

3.3 Battery management

Fig. 8 presents the battery management system. A battery package is a closed system, whose control system is much simpler than a fuel cell. The CVM monitors the voltage of each chip and the inner



(a)



(b)

Figure 7: Fuel cell control strategy (a) for the air supply system (b) for the heat management system

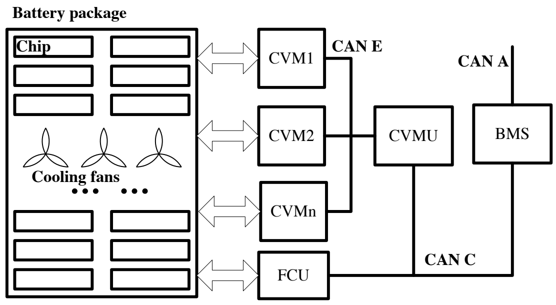
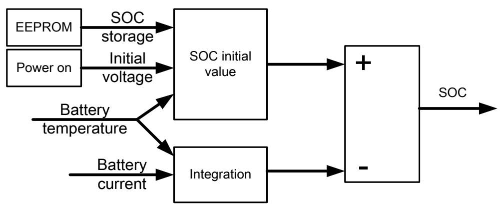


Figure 8: Battery management system

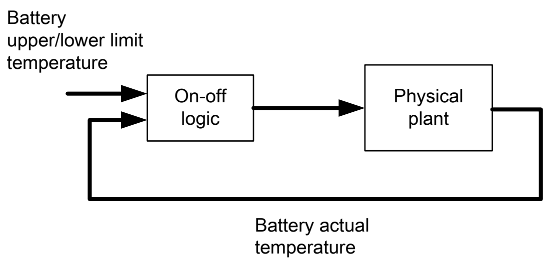
temperatures of sampled chips. When the temperature exceeds the critical level, fans fixed on the side/top of the package function to cool down the temperature.
The battery management strategy primary consists of two parts, the SOC estimating algorithm and the heat management strategy. The former is based on the Ampere-hour integration algorithm, as in Fig. 9 (a). The initial SOC is determined by two values: the initial voltage when the control system is powered on, and the stored SOC value in EEPROM. Battery temperature is regulated by several fans, which is controlled with on-off logic as in Fig. 9 (b).

4. Experimental results

Fig. 10 (a) ~ (e) indicate the experimental results of the networked hierarchical control system applied on a fuel cell hybrid city bus.



(a)



(b)

Figure 9: (a) SOC estimating algorithm on the basis of KF algorithm, (b) Heat management of battery packages

Fig. 10 (a) presents the vehicle velocity and the electric motor power. The velocity ranges from zero to 60km.h^{-1}. The peak power of the electric motor reaches 120kW, and part of the braking energy is recovered during decelerating. Fig. 10 (b) illustrates the power split between two fuel cell stacks and the battery package, and also shows the curve of battery SOC. In the energy management strategy, the battery is kept charge sustaining around 75%. At the beginning of the experiment, the battery SOC is larger than 75%. Thus, the battery provides the entire power. At about 2000s, the battery SOC decreases to 75%. After that, the fuel cell stacks provides the steady state component of vehicle power demand. And the battery supplies the dynamic power and recycles braking energy.

Fig. 10 (c) and (d) illustrate the work of the fuel cell control system for one stack. The air compressor is controlled according to the net output current with a feed forward + feedback algorithm. The net output current of the stack and the power of the air compressor are shown in Fig. 10 (c). The deionized water temperatures at the in-stack port and the out-stack port are shown in Fig. 10 (d). The tendencies of the two curves are almost the same. After starting the fuel cell system, the temperature increased linearly. When the temperature reached about 50 degree Celsius, the water pump and the radiator function, and the temperature is restricted in a suitable range, e.g. between 50 and 60 degree Celsius. The hydrogen pressure at the input port is kept at 55kPa during operation.

Since the battery package is a closed system, the status of each cell needs to be monitored. On the basis of CVM system, we can calculate the cell resistances. Fig. 10 (e) gives an example of the distribution diagram of cell resistances. There are totally 105 cells. About 34 cells obtain a 1 mΩ resistance. The cell resistances distribute between 0.8 mΩ and 1.3 mΩ. The average cell resistance is about 0.998 mΩ. The standard deviation of cell resistances is 0.071 mΩ. And the entire resistance of battery package is about 0.1Ω. This result means that, the batteryis at a well situation, and it can fulfill the requirements of public traffic applications.

5. Discussion and conclusion

Because of the complexity of the hybrid fuel cell powertrain, a networked hierarchical control system is necessary to coordinate the work of the entire system, to communicate with the remote monitoring system and to evaluate the status of components.

The networked control system obtains a hierarchical structure with four layers. The driver is in the top layer, and the vehicle control unit is in the second layer. The third and the fourth layers are designed for the fuel cell systems and the battery packages. The control strategies cover three aspects: a vehicle control strategy, a fuel cell control strategy and a battery management strategy.

The vehicle control strategy consists of an energy management strategy, a brake regeneration strategy and an active tolerant control strategy. The first keeps the fuel cell working in a quasi-steady state, and the battery charging sustaining. The second recovers energy so as to reduce hydrogen consumption. The third guarantee the normal work of the entire system even if malfunctions.

In the energy management strategy, the required power for fuel cell stacks are composed of three parts: the average power requirement of the electric motor power, the battery SOC compensation power and the vehicle auxiliary power. The difficulty is to predict the average power requirement of an electric motor. A low frequency pass filter is able to predict the power in some cases. However, if road conditions become complex, traffic information is necessary to be considered in algorithm.

The parallel brake regeneration strategy can recover part of the braking energy. However, the recycle ability is limited. An integrated system incorporating the functions of electric brake system, the ABS (Anti-lock Brake System) and the traditional friction brake system is necessary in future.

The active tolerant control system is absolutely necessary for electric vehicles. However, it needs lots of practical experiences to improve the strategy.

In the fuel cell control system, we introduce the control strategies for air supply system and cooling water system. Because the fuel cell is a passive power sources, a simple feed forward control strategy is used to control the air supply. A PI-feedback algorithm is developed to control the cooling water temperature. These strategies need to be further optimized basing on a nonlinear dynamic model.

In the battery management system, the SOC is estimated on the base of kalman filter (KF). We can deduce that, the essence of the KF algorithm is Ampere-hour integration algorithm. Thus, we use this method to calculate SOC. The battery temperature is controlled by several fans, which is regulated using a simple on-off strategy. The experiment shows the effectiveness of the proposed strategy.

Moreover, there are still several problems that are valuable to be studied further.

1) In some cases, the electric motor is not enough for traffic condition. Therefore, an automatic shift control system is necessary. The coordination

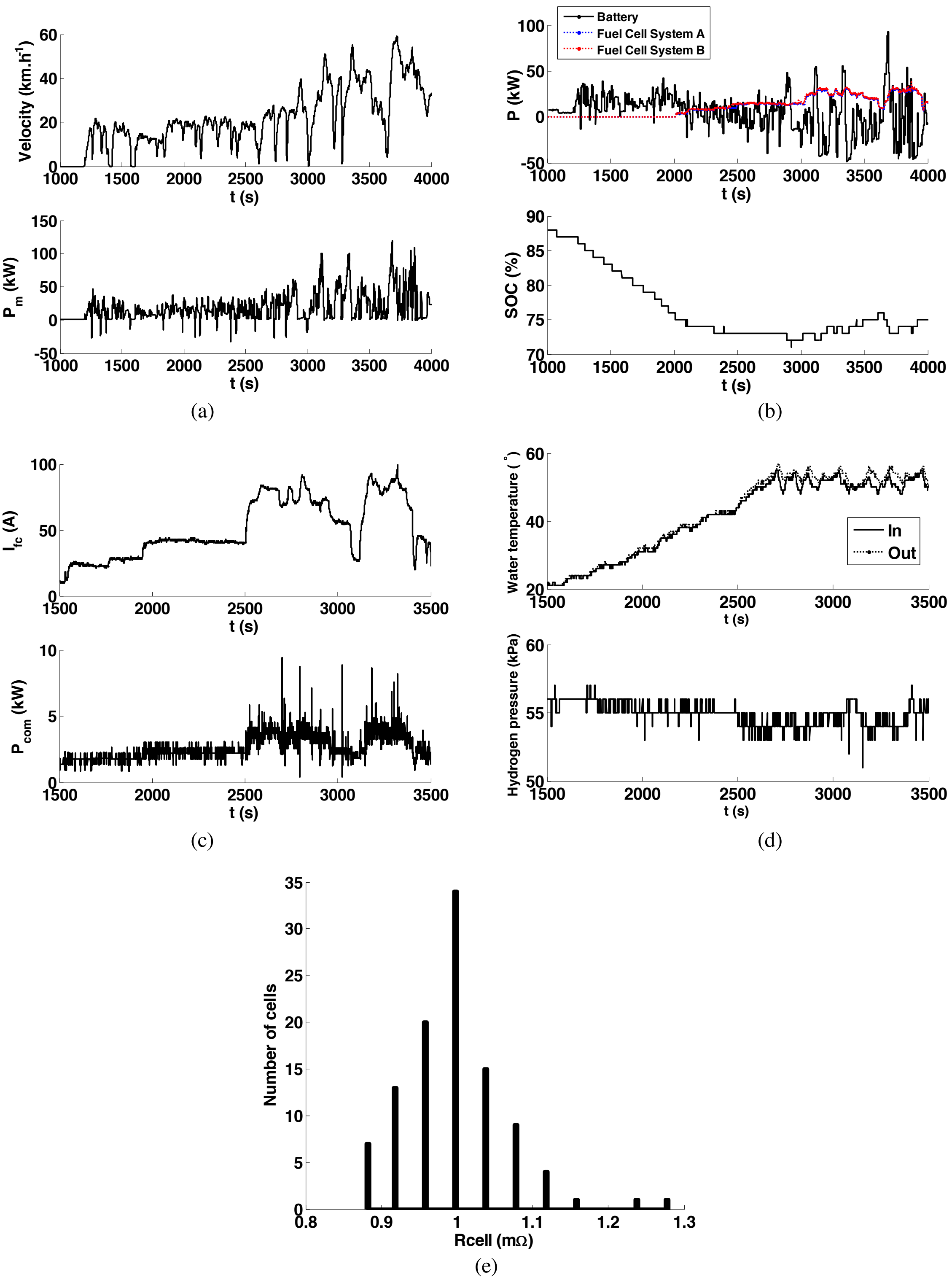


Figure 10: Experimental results (a) Velocity, electric motor input power (b) power split between two fuel cell stacks and battery, battery SOC (c) net output current of a fuel cell stack, air compressor power (d) in-stack and out-stack water temperature, hydrogen pressure at the input port (e) resistance distribution of battery cells

control problem between the electric motor and the AMT (Automated mechanical transmission) is coupled with the energy management strategy. This problem is valuable to be studied.

2) For the hybrid powertrain with two stacks, the power split strategy between the two stacks is also a problem. Currently, the power is split according to the cooling water temperature.

3) The starting process of the fuel cell stack needs to be studied. During this process, the output power should not too high, because the fuel cell is not able to output power when temperature is low. And it should not too low, because the temperature increases slowly if the output power is low. Thus, there will be an optimal starting process.

4) We use a Rint model to deduce the KF algorithm. The result is that, the KF algorithm is equivalent to the Ampere-Hour algorithm. However, if we use a more complex model, KF algorithm still has its advantage. The EKF (extended Kalman Filter) algorithm for SOC needs to be studied.

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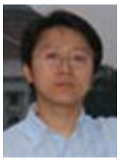

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