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Fuel cell output Power–oriented Control for a Fuel Cell Hybrid Electric Vehicle

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Abstract — **Under the pressure of air pollution and oil shortage of transportations, hydrogen as a renewable and clean energy gets more and more attentions from all over the world. There predicts that the 21^{st} century will be a hydrogen century. Nowadays, for the cost and not matured technology of fuel cell stack, hybrid system becomes the best solution. For a 5-ton fuel cell hybrid electric bus discussed in this paper, high-pressure PEMFC and high-power NiMH battery pack forms the hybrid system. In order to obtain the higher fuel efficiency and avoid the frequent charge & discharge of battery pack, a fuel cell output power-oriented control system is built. Also two kinds of control strategies for the control system are put forward as conventional Fuel cell output power oriented control, Fuel cell output power oriented control based on FCE loading and unloading equations. Their corresponding effects are compared based on simulation results. Finally, the fuel cell output power-oriented control system was applied on the fuel cell hybrid electric bus and the experiments are carried out. The Experimental results indicate that the fuel cell output power can follow the driver's requirement very well and the hybrid bus has a good hydrogen economy.**

I. INTRODUCTION

IN the 21 century, the auto fuel will be replaced by such regenerative resources as hydrogen and the power system with traditional internal combustion engine will be replaced by hybrid system and finally be replaced by fuel cell power system to realize multi-resources, electric driving and zero emission [1].The fuel cell regeneration system with hydrogen is regarded as the new generation generator. The power system with fuel cell system is regarded as the third generation system after steam engine and internal combustion engine [2].Under the background of great effort and support on developing clean and green vehicles, it is meaningful and valuable to do deep research on the key technologies of fuel cell vehicle.

For the high energy density and slow output response of fuel cell stack and long starting time, fuel cell engine only driving system is seldom used on vehicle except for overlarge fuel cell stack with expensive cost. Hybrid system becomes a solution with smaller fuel cell stack and high-power secondary sources, such as FCX from Honda uses Fuel Cell and Ultra capacitor, TUCSON FCEV from HYUNDAI uses Fuel Cell and LiPb or NiMH battery pack. Under the support of Ministry of Science and Technology of Chinese government, Beijing Institute of Technology takes great efforts on technology development of hybrid electric vehicles. For the fuel cell hybrid electric bus developed, high-pressure PEMFC and high-power NiMH battery pack forms the hybrid system. In order to obtain the higher fuel efficiency and avoid the frequent charge & discharge of battery pack, the active control for the fuel cell pack to follow the driver's pedal and the surplus peak power from NiMH battery pack passively is used.

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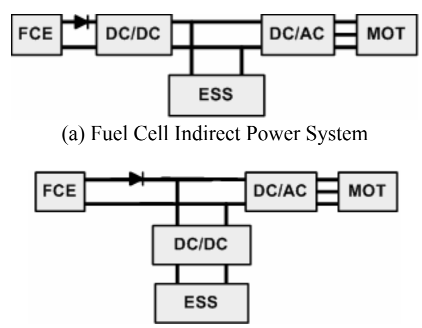
II. FUEL CELL HYBRID POWERTRAIN SYSTEM

A. Fuel cell Hybrid Power Train Structure

Mainly there are two kinds of fuel cell hybrid power train [3,4,5] as shown in fig.1.



(a) Fuel Cell Indirect Power System

(b) Fuel Cell Direct Power System

Fig.1 Fuel Cell Hybrid Power System

Where in fig.1, FCE means Fuel Cell Engine, DC/DC means DC/DC converter, DC/AC refers to motor controller; MOT means electric traction MOTor, ESS means Energy Storage System.

For fig.1 (a) named as fuel cell indirect power system, the FCE is connected with ESS in parallel after DC/DC converter, while for fig.1 (b) named as fuel cell direct power system, the FCE's output is directly inputted to DC/AC and the ESS is connected with the FCE's output in parallel after a bidirectional DC/DC. The power from the FCE and ESS is inputted to DC/AC together to drive the electric traction motor.

In fig.1 (a), for the DC/DC's existence, the FCE's output is separated with the bus line. This structure is better for the optimization and control of the FCE and is an economic selection for the fuel cell vehicle nowadays.

In fig.1 (b), for the FCE outputs power directly into DC/AC, the FCE must have good dynamic response to output enough power quickly to meet the vehicle's driving performance requirement and good voltage maintained performance to avoid the large voltage drop of bus line and the large torque drop of electric motor. On the other side, the FCE must be overlarge to avoid the possible damage.

For the fuel cell hybrid electric bus, we designed the power train as a kind of fuel cell indirect power system as fig.2 and the technical parameters is listed in table I.

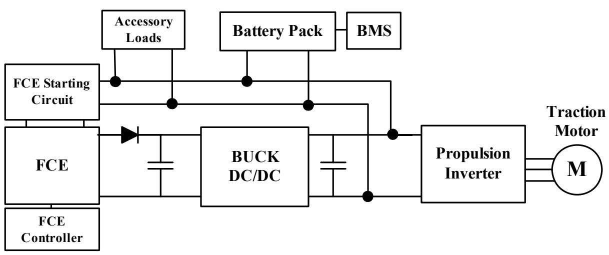


Fig.2. Fuel Cell Hybrid Electric Bus Power Train

TABLE I.
TECHNICAL PARAMETERS OF THE FUEL CELL HYBRID BUS

Item	Parameter	Value
Vehicle	Total Mass	4930 kg
	Curb Mass	4195 kg
ESS	Type	NiMH Battery Pack
	Rated Voltage	312V
	Rated Capacity	27 Ah
	Voltage range	260~390V
FCE	Rated Power	55kW
	Rated Voltage	336V
	Voltage range	310~450V
MOT	Rated Power	45kW
	Peak Power	77kW
DC/DC	Type	Buck
	Rated Power	55kW

B. High-pressured Fuel Cell Engine

To get better dynamic performance of fuel cell engine, high-pressured system [6] is used. At the rated power point, the polymer electrolyte fuel cell stack operates at 2.5~3.0 atm and 60~70^{o}C. In order to regulate the power output of fuel cell stack and recycle the surplus hydrogen for high fuel economy, the continuous variable speed control for the high-speed air compressor is special designed. The system efficiency including the auxiliary power loss is up to 47.6% and the power-increasing rate permitted is about 3kW/s when the air compressor in on regulation and the maximum power-increasing rate can be up to 5.5kW/s.The cold starting time for the fuel cell engine is experimented and less than 6.55s as shown in fig.3. The performance characteristic curves of the FCE are shown in fig.4.

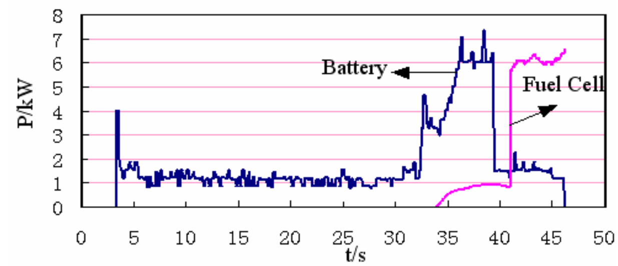


Fig.3. Cold Starting performance of the FCE

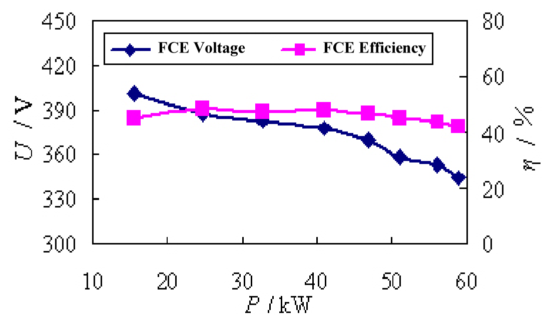


Fig.4. Power Curves of the FCE

C. DC/DC Converter

For the fuel cell indirect power system, the DC/DC converter functions as the output voltage or current regulator of the fuel cell and relieves the circuit relationship between fuel cell and battery pack. It is better and easy to realize the optimization control of fuel cell.

For the hybrid system, a buck converter is specially designed with the DC input voltage 300~420V and the output voltage DC 260~400V.The DC/DC converter's control logic is shown as fig.5. Its target output current or voltage is determined based on the hybrid system control strategy. Also the output voltage or current feedback, close-loop control and PWM+PWF control is applied.

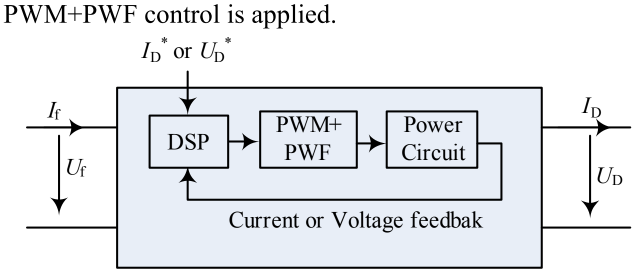


Fig.5. DC/DC converter's control logic

Where in fig.5, I_f is the fuel cell output current; U_f is the fuel cell output voltage; I_D is the output current of DC/DC converter; U_D is the output voltage of DC/DC converter; I_D^* is the target current required; U_D^* is the target voltage required.

D. NiMH Power Battery Pack

For the secondary energy storage system to power the auxiliary device, to heat, humidify the fuel cell stack during starting and to regenerate the braking energy, high-power NiMH Battery pack with the discharging characteristic MAP as shown in fig.6 and charging characteristic MAP as shown in fig.7 is selected and the management system is special designed with cooling system and special device to avoid overcharging, over discharging, electricity leakage and short circuit. The NiMH SOC is predicted with the PNGV dynamic model and calibrated with the characteristic MAP.

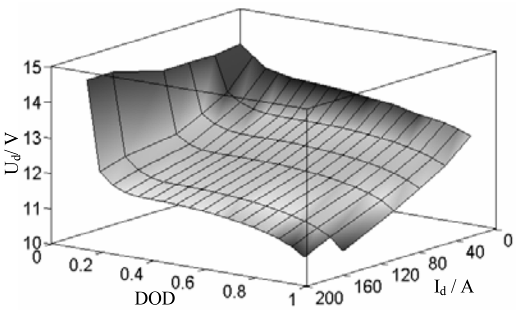


Fig.6. Discharging MAP of NiMH Battery

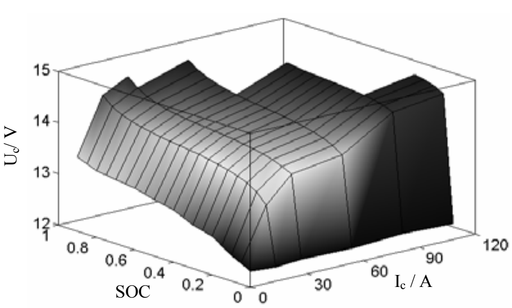


Fig.7. Charging MAP of NiMH Battery

III. Fuel Cell Active Control System

In order to realize the fuel cell active control and vehicle system control, a multi-layer networked control system is designed with CAN2.0B communication protocol and SAE J1939. The control network is shown in fig.8. The main controller receives the pedal signals from the driver. With the values of pedal, speed, the driving power required is calculated by look-up table of motor performance map. The target power of fuel cell engine is the sum of the driving power and the SOC-regulated power of battery pack. The target current of the DCDC converter is real-time calculated by the target driving power divided by the bus voltage. The air compressor's speed control is based on the target power of fuel cell engine.

$$P_d^* = f(l_d,\quad n_m) \tag{1}$$

$$I_D^* = \frac{P_d^*}{U_b} \tag{2}$$

$$P_b^* = f(\mathrm{SOC}) \tag{3}$$

$$P_f^* = P_d^* + P_b^* \tag{4}$$

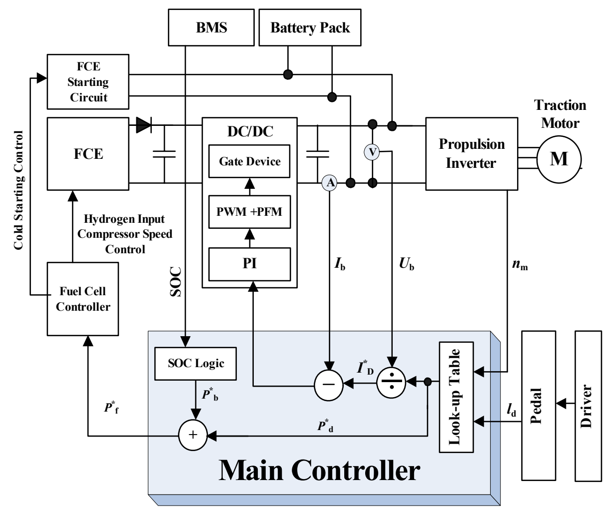


Fig.8. Fuel cell active control system

Where in fig.8 and eq.(1)~(4), n_m is motor speed, l_d is the pedal angle, U_b is the bus line DC voltage, I_b is the bus line current, P^*_d is the target driving power, P^*_b is target power of battery pack, P^*_f is the target power of fuel cell engine.

For the FCE, the limitation model is set to make sure that the FCE always works in proper condition and to avoid possible dynamic damage.

The FCE target power limitation model:

$$P_{f\_min} \le P_f^* \le P_{f\_max} \tag{5}$$

Where P_{f_min} is the minimum power of the FCE, P_{f_max} is the maximum power of the FCE.

The FCE loading dynamic limitation model:

$$P_f(k+1) = \min\left(P_f(k) + \Delta P_f,\quad P_f^*\right) \tag{6}$$

$$\Delta P_f = \begin{cases} 3 & \lambda_c = 0 \\ \min\left(\left|P_{f\_max}(\lambda) - P_f(k)\right|,\quad 5.5\right) & \lambda_c = 1 \end{cases} \tag{7}$$

The FCE unloading dynamic limitation model:

$$P_f(k+1) = \max\left(P_f^*,\quad P_{f\_min}\right) \tag{8}$$

Where, k, k+1 means the kth, (k+1)th second, λ_c refers to the condition of FCE compressor, λ_c=0 means the FCE compressor is in dynamic adjusting, and λ_c=1 means the FCE compressor is in steady state, ΔP_f refers to the power loading or unloading rate, $P_{f\_max}(\lambda)$ is the maximum power permitted when the FCE compressor is in steady state λ.

IV. System Control Strategy

From eq.(4), in order to properly determine the target power of Fuel cell and at the same time to realize the active control of fuel cell engine, it becomes very important to design a suitable and reasonable system control strategy. There are two kinds of control strategies as fuel cell output energy-oriented control and fuel cell output power-oriented control [7]. For the fuel cell engine we designed has a good power response and dynamic characteristics, the fuel cell output power-oriented control is preferred [8].

A. Conventional fuel cell output power oriented control strategy

The basic idea for the conventional fuel cell output power oriented control strategy is as following: setting the FCE as the main power sources and controlling the FCE's output power to follow the vehicle's driving power requirement at some extent. The FCE is working on nearly for all of the driving time expect for the first cold start and small driving power requirement while battery pack is at high SOC. The control logic based on thresholds is shown as fig.9.

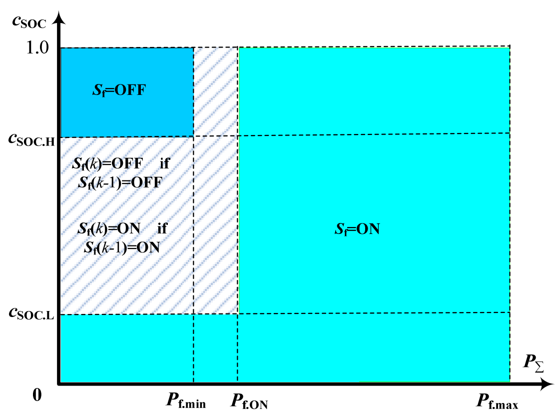


Fig.9. Control Logic for the conventional Fuel cell output power oriented Control Strategy

The target power of FCE is calculated as:

$$P_{\mathrm{f}}^{*}(k+1)=\begin{cases}0 & \begin{array}{l}\left(c_{\mathrm{SOC}}(k)\geq c_{\mathrm{SOC.H}} \quad AND \quad P_{\mathrm{d}}(k)\leq P_{\mathrm{f.min}}\right)\\ OR \begin{pmatrix} c_{\mathrm{SOC}}(k)\geq c_{\mathrm{SOC.H}} \quad AND \\ P_{\mathrm{f.ON}}\geq P_{\mathrm{d}}(k)>P_{\mathrm{f.min}} \quad AND \\ S_{\mathrm{f}}(k)=\mathrm{OFF}\end{pmatrix}\\ \begin{pmatrix} c_{\mathrm{SOC.L}}\leq c_{\mathrm{SOC}}(k)<c_{\mathrm{SOC.H}} \\ AND \quad P_{\mathrm{d}}(k)\leq P_{\mathrm{f.ON}} \\ AND \quad S_{\mathrm{f}}(k)=\mathrm{OFF}\end{pmatrix}\end{array}\\[2ex] \dfrac{P_{\mathrm{d}}^{*}(k)-P_{\mathrm{B}}^{*}(k+1)}{\eta_{\mathrm{D}}} & \begin{array}{l}\begin{pmatrix} c_{\mathrm{SOC}}(k)\geq c_{\mathrm{SOC.H}} \quad AND \\ P_{\mathrm{f.ON}}\geq P_{\mathrm{d}}(k)>P_{\mathrm{f.min}} \quad AND \quad S_{\mathrm{f}}(k)=\mathrm{ON}\end{pmatrix}\\ OR \begin{pmatrix} c_{\mathrm{SOC.L}}\leq c_{\mathrm{SOC}}(k)<c_{\mathrm{SOC.H}} \quad AND \\ 0\leq P_{\mathrm{d}}(k)\leq P_{\mathrm{f.ON}} \quad AND \quad S_{\mathrm{f}}(k)=\mathrm{ON}\end{pmatrix}\\ \left(c_{\mathrm{SOC}}(k)<c_{\mathrm{SOC.L}}\right)\\ \left(P_{\mathrm{d}}(k)>P_{\mathrm{f.ON}}\right)\end{array}\\[2ex] P_{\mathrm{f.min}} & \left(P_{\mathrm{d}}(k)\leq 0 \quad AND \quad S_{\mathrm{f}}(k)=\mathrm{ON}\right)\end{cases} \tag{9}$$

Where in fig.9 and eq. (9), c_{SOC} is the state of charge of battery pack; $c_{\mathrm{SOC\_H}}$, $c_{\mathrm{SOC\_L}}$ are the maximum and minimum c_{SOC} predetermined; η_{D} is the efficiency of DC/DC converter; $P_{\mathrm{f.min}}$ is the minimum power of fuel cell engine predetermined; $P_{\mathrm{f.ON}}$ is the power at which the fuel cell is started; s_{f} is the working state of fuel cell engine.

The battery pack's target regulation power is calculated as:

$$P_{\mathrm{B}}^{*}(k+1)=\begin{cases}P_{\mathrm{B.max}} & c_{\mathrm{SOC}}(k)>c_{\mathrm{SOC.H}}\\ P_{\mathrm{B.max}}\dfrac{c_{\mathrm{SOC}}(k)-c_{\mathrm{SOC.t}}}{c_{\mathrm{SOC.H}}-c_{\mathrm{SOC.t}}} & c_{\mathrm{SOC.t}}\leq c_{\mathrm{SOC}}(k)\leq c_{\mathrm{SOC.H}}\\ P_{\mathrm{B.min}}\dfrac{c_{\mathrm{SOC}}(k)-c_{\mathrm{SOC.t}}}{c_{\mathrm{SOC.L}}-c_{\mathrm{SOC.t}}} & c_{\mathrm{SOC.L}}\leq c_{\mathrm{SOC}}(k)\leq c_{\mathrm{SOC.t}}\\ P_{\mathrm{B.min}} & c_{\mathrm{SOC}}(k)<c_{\mathrm{SOC.L}}\end{cases} \tag{10}$$

Where in eq.(10), $P_{\mathrm{B.max}}$, $P_{\mathrm{B.min}}$ are the maximum discharging and minimum charging power permitted of Battery pack; $c_{\mathrm{SOC.t}}$ is the target c_{SOC}.

B. Fuel cell output power oriented control strategy based on FCE loading and unloading equations

The basic control logic is similar to the fuel cell output power oriented control strategy as just mentioned above, but there has some new control characteristics as following.

- If $c_{\mathrm{SOC}} > c_{\mathrm{SOC.t}}$, the battery regulation power is zero and the battery actual output power is the power difference between P_{d} and P_{f};
- If $c_{\mathrm{SOC}} \leq c_{\mathrm{SOC.t}}$, the battery regulation charging power is considered and the target fuel cell power is the sum of driving power and charging power;
- When the vehicle is braking, the fuel cell works at the minimum power and charges the battery pack with the regenerative braking;
- The fuel cell engine works on nearly all of the driving time expect for the over high SOC battery pack and small driving power requirement at the first cold starting.

The corresponding control logic is:

$$P_{\mathrm{B}}^{*}(k+1)=\begin{cases}P_{\mathrm{d}}^{*}(k) & c_{\mathrm{SOC}}(k)>c_{\mathrm{SOC.H}} \quad AND \quad P_{\mathrm{d}}^{*}(k)\leq P_{\mathrm{f.ON}}\\ P_{\mathrm{d}}^{*}(k)-P_{\mathrm{f}}^{*}(k+1)\cdot\eta_{\mathrm{D}} & c_{\mathrm{SOC.t}}\leq c_{\mathrm{SOC}}(k)\leq c_{\mathrm{SOC.H}}\\ P_{\mathrm{B.min}}\dfrac{c_{\mathrm{SOC}}(k)-c_{\mathrm{SOC.t}}}{c_{\mathrm{SOC.L}}-c_{\mathrm{SOC.t}}} & c_{\mathrm{SOC.L}}\leq c_{\mathrm{SOC}}(k)\leq c_{\mathrm{SOC.t}}\\ P_{\mathrm{B.min}} & c_{\mathrm{SOC}}(k)<c_{\mathrm{SOC.L}}\end{cases} \tag{11}$$

$$P_{\mathrm{f}}^{*}(k+1)=\begin{cases}0 & c_{\mathrm{SOC}}(k)>c_{\mathrm{SOC.H}} \quad AND \quad P_{\Sigma}^{*}(k)\leq P_{\mathrm{f.ON}}\\ P_{\mathrm{f.min}} & c_{\mathrm{SOC.L}}\leq c_{\mathrm{SOC}}(k)\leq c_{\mathrm{SOC.H}} \quad AND \quad P_{\Sigma}^{*}(k)<0\\ \dfrac{P_{\mathrm{d}}^{*}(k)-P_{B}^{*}(k+1)}{\eta_{\mathrm{D}}} & c_{\mathrm{SOC}}(k)\leq c_{\mathrm{SOC.t}} \quad AND \quad P_{\Sigma}^{*}(k)\geq 0\\ \max\left\{P_{\mathrm{f.min}},\ \min\left\{P_{\Sigma}^{*}(k),\ P_{\mathrm{f\cdot max}}(k)\right\}\right\} & c_{\mathrm{SOC.t}}\leq c_{\mathrm{SOC}}(k)\leq c_{\mathrm{SOC.H}} \quad AND \quad P_{\Sigma}^{*}(k)>0\end{cases} \tag{12}$$

C. Comparison based on simulation results

In order to do a comparison between the two controls strategies put forward above, simulation experiments are carried out under the Matlab/Simulink for the fuel cell hybrid bus we designed with the parameters as Table I. The driving cycle input is shown as fig.11. The initial c_{SOC} is 0.7 and c_{SOC_H}=0.8, c_{SOC_L}=0.4, c_{SOC_t}=0.6.

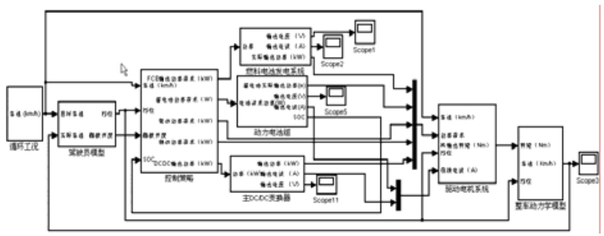


Fig. 10. Simulation model of the fuel cell hybrid bus

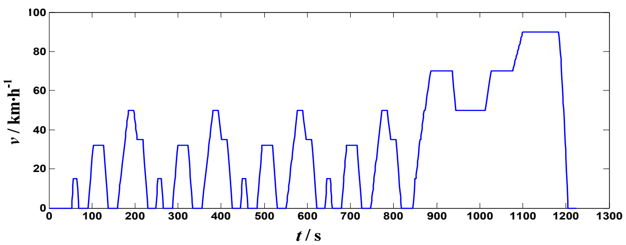
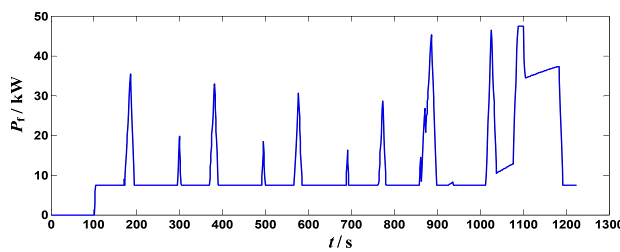
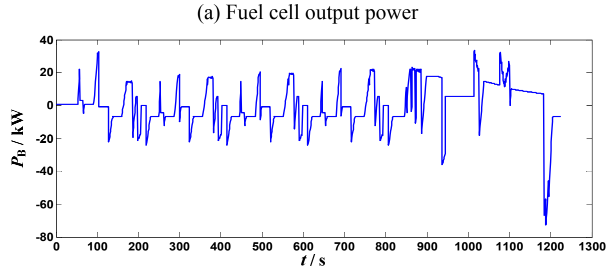


Fig.11. Driving cycle for the simulation experiments

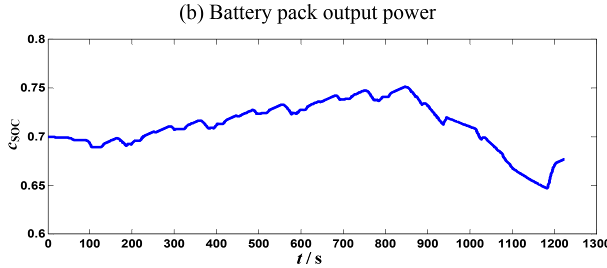
For the conventional fuel cell output power oriented control strategy, the controlling result is as fig.12.



(a) Fuel cell output power



(b) Battery pack output power

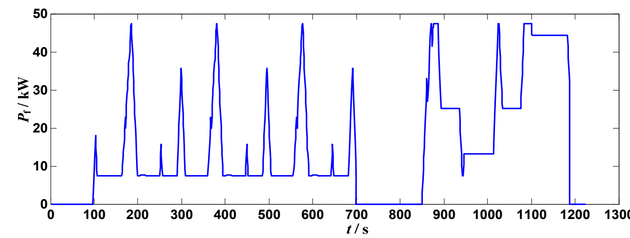


(c) Battery pack SOC

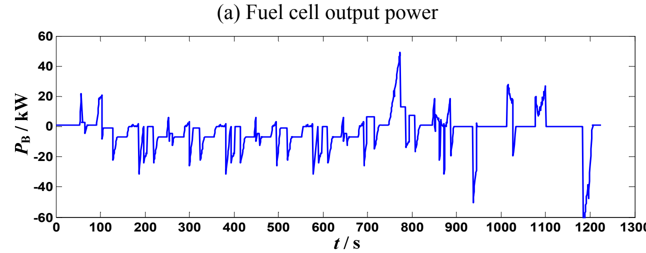
Fig. 12. Control results of the conventional fuel cell output power oriented control strategy

For the initial c_{SOC} is larger that c_{SOC_t}, the battery pack is discharged passively according to the control logic, at the same time the FCE works at lower load state inefficiently. The final c_{SOC} is 0.677 and the hydrogen economy is 2.7144kg/100km after consideration the energy change of battery pack.

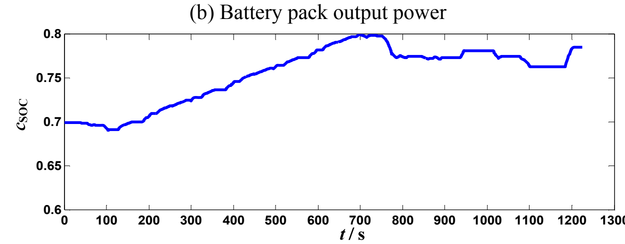
For the control strategy of fuel cell output power oriented control based on FCE loading and unloading equations, the controlling result is as fig.13.



(a) Fuel cell output power



(b) Battery pack output power



(c) Battery pack SOC

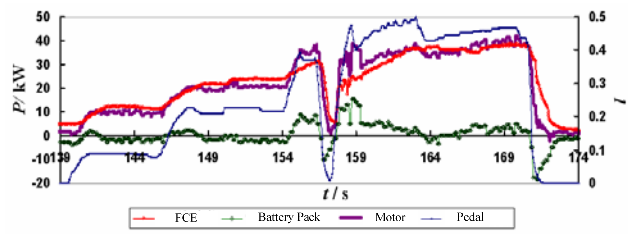
Fig. 13. Control results of the fuel cell output power oriented control strategy based on FCE loading and unloading equations

For the initial c_{SOC} is larger than c_{SOC_t}, the driving power is mainly from FCE while the battery pack only output peak power passively. Compared with the conventional fuel cell output power oriented control strategy, the FCE load is increased and the efficiency is improved. The final c_{SOC} is 0.785 and the hydrogen economy is 2.5054kg/100km after consideration the energy change of battery pack.

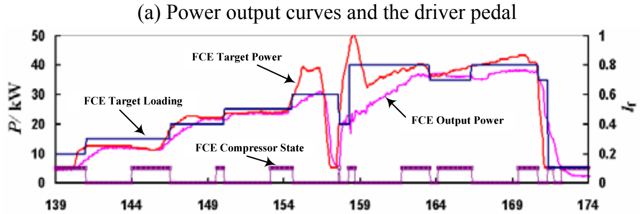
V. System Experiment

We applied the control strategy of fuel cell output power oriented control based on FCE loading and unloading equations on the fuel cell hybrid bus we designed as shown in fig. 14 and the vehicle experiment results are shown as fig. 15. It is easy to find from fig.15(a) that the power output of FCE follows the driver pedal and driving motor power very well. The battery pack only outputs peak power during such period that driver pedal suddenly changes with the maximum discharging power of 17.71kW and charging power of -18.30 kW. The output characteristics of FCE meets the limitation equations predetermined very well as fig.15(b). For the target c_{SOC} of battery pack is 0.60, the bus line DC voltage is maintained at a high level of 360V as fig.15(c) and the better power output characteristics of motor is safeguarded. The experiment lasts 1658s and drives 13.48km, the average hydrogen economy is 2.464kg/100km.

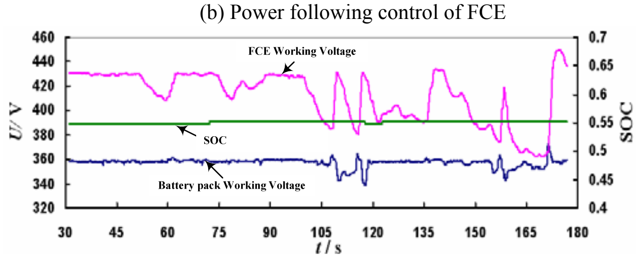
Fig.14. Fuel cell hybrid bus



(a) Power output curves and the driver pedal



(b) Power following control of FCE



(c) Voltage and SOC curves

Fig.15. The vehicle experiment results

VI. Conclusions

The fuel cell indirect drive hybrid system is one of the practical power train topology for the nowadays technologies.

A fuel cell active control system is put forward and corresponding equations are established. The FCE target power limitation model and the FCE loading dynamic limitation model are analyzed and built.

The fuel cell output power-oriented control is preferred and two corresponding control strategies are put forward as the conventional fuel cell output power oriented control strategy and the control strategy of Fuel cell output power oriented control based on FCE loading and unloading equations. The general performance for the two control strategies are simulated and compared with the forward simulation models and the control strategy of Fuel cell output power oriented control based on FCE loading and unloading equations gets the better performance.

We applied the control strategy of fuel cell output power oriented control based on FCE loading and unloading equations on the fuel cell hybrid bus we designed. The experiment results show that the power output of fuel cell engine follows the driver pedal and driving motor power very well and the battery pack only outputs peak power passively, the average hydrogen economy of the hybrid fuel cell bus is 2.464kg/100km.

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