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Modeling and Simulation of PEM Fuel Cell / Battery Hybrid Vehicle

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Abstract: This paper describes *modeling of a hybrid power system* that supplies energy to an electric vehicle based on a hybrid system that uses a proton exchange membrane (PEM) fuel cell as a primary energy source and a battery pack as an ancillary energy storage system. *A threshold approach* has been employed for *power control.* When the power required by the vehicle exceeds a threshold, the battery works with the fuel cell to satisfy the dynamic response of vehicle. Otherwise the fuel cell works alone with regenerative braking enabling recharging of battery capacity. The proposed model has been simulated and tested using Matlab/Simulink software, which predicts that good battery SOC (state of charge) recovery and lower hydrogen consumption levels can be achieved when *Federal Urban Driving Schedule (FUDS) and New European Driving Cycle (NEDC) protocols* are employed.

Keywords: FCHV; power control; modeling and simulation; fuel consumption

燃料电池/蓄电池混合动力汽车建模与仿真

孙桂芝 [1]，Sam Park[2]，林忠玲 [1]

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摘要: 对以燃料电池为主电源，蓄电池为辅助电源的*混合动力汽车进行建模*。采用*设定阈值*的方法进行*功率控制*。当车辆需要的功率超过设定阈值时，蓄电池与燃料电池共同输出功率。否则，由燃料电池单独输出功率，制动能量回收为蓄电池充电。应用 MATLAB/Simulink 软件对 *FUDS 和 NEDC 两种驾驶循环模式进行仿真*，结果显示蓄电池的存电状态可以获得良好的恢复，氢气消耗量大幅度降低。

关键词: 燃料电池混合动力汽车；功率控制；建模仿真；燃油消耗
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Introduction

Fuel cell hybrid vehicles (FCHV) are one of the most promising candidates for decreasing air pollution produced from the urban transportation sector, because they result in zero gas emissions and improved energy conservation levels[1-2]. Polymer Electrolyte Membrane (PEM) Fuel Cells (also known as Proton Exchange Membrane Fuel Cells) exhibit high power densities, employ solid electrolytes, have long cell and stack lives, and experience low

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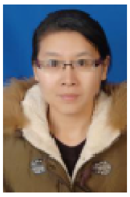

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Biography: Sun Guizhi (1981-), female, Yantai, Shandong, Chins, master, lecturer, research interests: fuel cell hybrid vehicle; Sam Park (1972-), male, Korea, PHD, associate professor, research interests: fuel cell battery, electrochemical power conversion; Lin Zhongling (1970-), female, Yantai, Shandong, China, master, lecturer. research interests: fuel cell hybrid vehicle.

corrosion levels[3]. A number of electric vehicle systems using PEM fuel cells for energy supply have been developed, however, their performance levels are currently limited by the rates of their electrochemical reactions. Hybridization with additional energy sources, such as capacitors or battery packs, can address transient power demand fluctuations, especially when a vehicle undergoes hard acceleration. These supplementary energy sources can also supply significant energy savings, because they enable energy to be recovered through regenerative braking processes that can be used to minimize hydrogen consumption. This paper now describes an energy management algorithm that can be used to model the performance of a hybrid power system in an electric vehicle. This hybrid system employs a proton exchange membrane (PEM) fuel cell as a primary energy source, supplemented by a battery pack as an ancillary energy storage system that is predicted to result in improved power output in in electric vehicles.

1 Modeling of fuel cell hybrid vehicle

Fuel cells used in hybrid vehicles are comprised of a number of components, including a fuel cell stack, battery pack, bidirectional DC/DC converter, electric motor, controller and gear box.

1.1 Fuel Cell Stack Voltage Model

The stack voltage of a fuel cell can be calculated as a function of stack current, whose current-voltage relationship is determined from a polarization curve (cell voltage versus cell current density). The fuel cell stack consists of multiple fuel cells connected in series, with the stack voltage taken as the sum of the individual cell voltages. This study assumes that these cells are identical, which enables the stack voltage to be calculated using the following equations[3]:

$$V_{st} = n \times V_{fc}$$

$$i_{fc} = I_{st} / A_{fc}$$

where, V_{st}: fuel cell stack voltage (V)

V_{fc}: cell voltage (V)

i_{fc}: cell current density (A/cm^2)

I_{ST}: stack current (A)

The fuel cell voltage can then be calculated using a combination of physical and empirical relationships, given by[4]:

$$V_{fc} = E_{fc} - V_{act} - V_{ohm} - V_{conc}$$

The open circuit voltage E_{fc} can be calculated from the energy balance between the reactants and products and the Faraday Constant using the following equation[5]:

$$E_{fc} = 1.229 - 8.5 \times 10^{-4}(T_{fc} - 298.15) + 4.3085 \times 10^{-5} T_{fc}[\ln(P_{H_2}) + \frac{1}{2}(P_{O_2})]$$

Where: V_{act}: the activation voltage losses (V); V_{ohm}: ohmic voltage losses (V); V_{conc}: concentration of voltage losses (V); E_{fc}: the open circuit voltage (V); P_{H_2}: the partial pressure of hydrogen (atm); P_{O_2}: the partial pressure of oxygen (atm).

Activation voltage losses arise from electrons migrating from the anode and reacting at the cathode[6], with the relationship between activation voltage losses and current density described by the Tafel equation:

$$V_{act} = v_0 + v_a(1 - e^{-c_1 i})$$

Activation voltage losses are also dependent on temperature and oxygen partial pressures[5,7], with the values of v_0, v_a and c_1, and their dependency on oxygen partial pressure and temperature determined from nonlinear regression of experimental data, using the following equations:

$$v_0 = 0.279 - 8.5\times10^{-4}(T_{fc} - 298.15) + 4.3085\times 10^{-5}T_{fc}[\ln(\frac{p_{ca} - p_{sat}}{1.01325}) + \frac{1}{2}\ln(\frac{0.1173(p_{ca} - p_{sat})}{1.01325})]$$

$$v_a = (-1.618\times10^{-5}T_{fc} + 1.618\times10^{-2})(\frac{p_{O_2}}{0.1173} + p_{sat})^2 + (1.8\times10^{-4}T_{fc} - 0.166)(\frac{p_{O_2}}{0.1173} + p_{sat}) + (-5.8\times10^{-4}T_{fc} + 0.5736)$$

where, v_0: voltage drop at zero current density (V); v_a: constant dependent on experiments(V); p_{ca}: total cathode pressure (atm); p_{sat}: saturation pressure (atm).

Ohmic voltage losses arise due to resistance of the polymer membrane to the transfer of protons and the resistance of the electrodes and collector plates to the transfer of electrons. Voltage drops are proportional to the current given by the following equation:

$$v_{ohm} = i_{fc}\cdot R_{ohm}$$

The resistance R_{ohm} depends strongly on membrane humidity[8] and cell temperature[9]. The ohmic resistance is proportional to membrane thickness t_m and inversely proportional to the membrane conductivity $\sigma_m(\lambda_m, T_{fc})$ [10-11], which may be calculated using the following equations:

$$\sigma_m = (b_{11} - b_{12})\exp(b_2(\frac{1}{303} - \frac{1}{T_{fc}}))$$

where, R_{ohm}: resistance of fuel cell (Ω); σ_m: membrane conductivity $(\Omega\cdot\mathrm{cm})^{-1}$.

T_m, b_{11} and b_{12} values for a Nafion 117 membrane were used[11], with b_2 values adjusted to fit fuel cell data. Concentration voltage losses are caused by increased losses that occur at high current densities. Significant decreases in reactant concentrations also occur due to high reactant consumption and head losses that occur when flow rates are high. Approximate concentration losses can be calculated using the following equations[12]:

$$v_{conc} = i_{fc}(c_2\frac{i_{fc}}{i_{\max}})^{c_3}$$

where, c_1=10, c_3=2, $i_{\max}$=2.2, b_{11}=0.05139, b_{12}=0.00326, b_2=350.

$$c_2 = (7.16\times10^{-4}T_{fc} - 0.622)(\frac{p_{O_2}}{0.1173} + p_{sat}) + (-1.45\times10^{-3}T_{fc} + 1.68)$$

for $\frac{p_{O_2}}{0.1173} + p_{sat} < 2$

Where

$$c_2 = (8.66\times10^{-5}T_{fc} - 0.068)(\frac{p_{O_2}}{0.1173} + p_{sat}) + (-1.6\times10^{-4}T_{fc} + 0.54)$$

for $\frac{p_{O_2}}{0.1173} + p_{sat} \ge 2$

And hydrogen consumption can be calculated using the following equation:

$$W_{H_2} = M_{H_2}\frac{nI_{st}}{2F}$$

Where, W_{H_2}: the mass of reacted hydrogen (g);

W_{H_2}: hydrogen molar mass (g/mol);

The parameters used for the fuel cell stack are described in Tab. 1.

Tab. 1 Parameter values of the fuel cell stack

Name	Value	Description
n	210	number of cells in the stack
A_{fc}	678	cell effective area (cm^2)
T_{fc}	353	fuel cell stack temperature (K)
F	96 487	Faraday constant
T_m	0.0127 5	membrane thickness of fuel cell (cm)

The simulation current-voltage characteristic of the PEM Fuel Cell Stack model used in this study is shown in Fig.1

1.2 Battery Model

The battery used in the fuel cell hybrid vehicle can be represented using the basic equivalent circuit shown in Fig. 2[13].

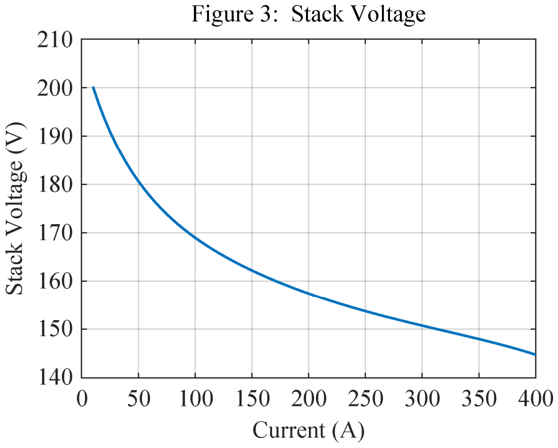

Fig. 1 Plot of stack voltage-current of the PEM fuel cell

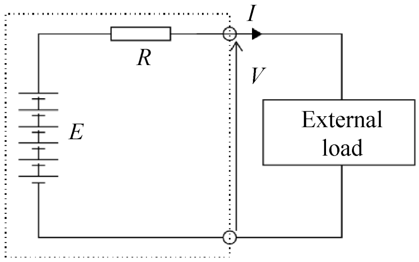

Fig. 2 Simple equivalent circuit model of a battery

The internal resistance of a lead acid battery can be estimated using the following equation:

$$R = n_b \times \frac{0.022}{c_{10}}$$

where, R: the internal resistance of the discharging battery(Ω)

This model enables the following four equations to be used to calculate the open circuit voltage using Equation (1):

$$E = n_b \times (2.15 - DoD) \times (2.15 - 2.00)$$
$$DoD_n = CR_n / C_p$$
$$C_p = I^k T$$
$$CR_{n+1} = CR_n + \frac{\delta_t \times I^k}{3600} \tag{1}$$

The total charge supplied by the battery to the vehicle can then be determined using the following equation:

$$CS_{n+1} = CS_n + \frac{\delta_t \times I}{3600}$$

When a specific electrical power value is required, the current flows produced by the battery can be calculated using the following equation:

$$I = \frac{E - \sqrt{E^2 - 4RP_b}}{2R}$$

When the vehicle brakes, the issue of regenerative braking needs to be considered, with a fixed amount of power being available to be recaptured by the battery. Therefore, the current flowing into the battery may be given by equation:

$$I_{ch} = \frac{-E + \sqrt{E^2 - 4R_{ch}P_{ch}}}{2R_{ch}}$$

When the battery is fully charged, Equation (1) is equivalent to Equation (2):

$$CR_{n+1} = CR_n - \frac{\delta_t \times I}{3600} \tag{2}$$

where, *E*: the open circuit voltage of the battery (V); *DoD*: the depth of discharge of the battery; DoD_n: the depth of discharge of battery for the nth step of the simulation; CR_n: the total charge removed from the battery; C_p: the Peukert Capacity (A·h); *I*: the discharge current of the battery (A); *T*: the time that the battery discharge takes until it becomes flat (hour); δ_t: the time step between calculations (s); I_{ch}: the charge current of the battery (A); CS_n: the charge supplied by the battery to the vehicle; P_b: the power output from the battery (W); R_{ch}: the internal resistance of the battery when charging (Ω); P_{ch}: the charge power input to the battery (W).

The state of charge (*SOC*) of a battery is a dimensionless parameter that relates existing power capacity to the theoretical capacity of the battery. As the battery is discharged and charged, the *SOC* is equivalent to the relative amount of energy that has been removed, or added to the battery, expressed as a normalized ratio. Therefore, the *SOC* of the battery system can be calculated using the following equation[13]:

$$SOC(t)=\frac{actualbatterych\arg e(t)}{totalbatterych\arg e}$$

Where, $SOC(t)$: the state of charge of the battery at time t.

The parameters used for the battery pack are given in Tab. 2.

Tab. 2 Parameter values of the battery pack

Name	Value	Description
n_b	30	number of cells in the battery
C_{10}	25	amphour capacity at the 10hour rate (Ah)
k	1.12	Peukert coefficient
$\mathrm{SOC}_{\mathrm{init}}$	0.8	initial state of charge of the battery
SOC_{low}	0.5	the lowest value of SOC

1.3 Electric Vehicle Model

Modeling and simulation of the power input to the electric vehicle was carried out using a Matlab/ Simulink environment incorporating equations for vehicle dynamics and battery modeling[14].

(1) Rolling resistance force

The rolling resistance is primarily due to the friction of the vehicle tire on the road, which can be calculated using the following equation:

$$F_{rr}=\mu_{rr}mg$$

(2) Aerodynamic drag was calculated using the following equation:

$$F_{ad}=\frac{1}{2}\rho AC_dV_2$$

(3) Hill climbing forces were calculated using the following equation:

$$F_{hc}=mg\sin(\beta)$$

(4) Acceleration forces were calculated using the following equation:

$$F_{la}=ma$$

The total tractive effort is the sum of all these forces, which can be calculated using the following equation:

$$F_{te}=F_{rr}+F_{ad}+F_{hc}+F_{la}$$

The power required by the vehicle can then be calculated using the following equation:

$$P_{req}=F_{te}\cdot v$$

where, F_{rr}: the rolling resistance force (N); F_{ad}: aerodynamic drag (N); v: vehicle velocity (m/s); F_{hc}: the hill climbing force (N); F_{la}: acceleration force (N); a: Vehicle acceleration (m/s^2); F_{te}: the total tractive force of vehicle (N).

The parameters of the vehicle are given in Tab. 3[14].

Tab. 3 Parameter values for the vehicle and motor

Name	Value	Description
m	1236	vehicle mass (kg)
ρ	1.25	density of air (kg/m^3)
A	1.8	frontal area (m^2)
C_d	0.19	drag coefficient
β	0	road slope angle (rad)
g	9.8	gravitational acceleration (m/s^2)
μ_{rr}	0.0048	coefficient of rolling resistance
k_w	5.0×10^{-6}	windage loss coefficient
k_c	0.3	copper loss coefficient
k_i	0.01	iron loss coefficient
C	600	constant losses that apply at any speed
η_g	0.95	efficiency of the gear box

The power required by the fuel cell hybrid vehicle is a sum of the power provided by the fuel cell and the storage battery. The law of conservation of energy can be used to construct the power flow chart shown in Fig.3, which can be used to describe power flow to the wheels of the vehicle (see Fig. 3)[14].

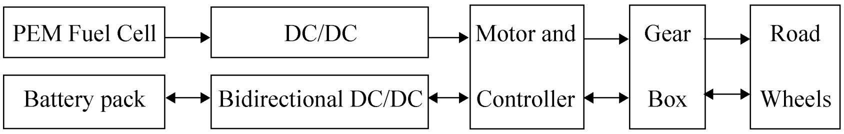

Fig. 3 Energy flow in vehicle incorporating regenerative braking

1.4 Powertrain Model

When the vehicle is being driven, its power can be calculated using the following equations:

$$P_{m\_in} = \frac{P_{m\_out}}{\eta_m}$$

The power required to drive the vehicle (supplied by the energy source) is equal to the power of the motor. It is assumed that the efficiency of both DC/DC converters is ideal (100%), with p_{req} then being calculated using the following equation:

$$P_{req} = P_{m\_in}$$

When braking, the overall motor power becomes negative, which results in power flowing in the reverse direction. This enables the battery pack to be charged using regenerative braking power, whose value can be calculated using the following equations:

$$P_{m\_in} = P_{m\_out} \times \eta_m$$

$$P_{m\_out} = P_{te} \times \eta_g$$

$$\eta_m = \frac{T_m \omega}{T_m \omega + k_c T^2 + k_i \omega + k_{\omega^3} + c}$$

where, P_{m_in}: power transferred into the motor (w); P_{m_out}: power out of the motor (w); T_m: motor torque (N·m); P_{req}: power supplied by the energy source (w); η_m: efficiency of the motor; ω: motor angular speed (rad/s); P_{th}: threshold power with hybridization (w).

Therefore, the battery will be charged if the SOC value is less than the SOC_{high} value.

2 Energy Management

The fuel cell voltage is highest when no current is flowing, with voltage levels decreasing with increasing current. High current levels can lead to reactant starvation, so the current (and power) drawn from the fuel cell stack needs to be limited. Therefore, when the power required by vehicle is less than a specific threshold value P_{th}, or SOC is lower than the preset lowest value SOC_{low} (0.5), the fuel cell supplies power to the vehicle, and the fuel cell stack supplies power to charge the battery. Alternatively, when SOC is higher than SOC_{low} (0.5), the fuel cell supplies power equal to P_{th}, with the remainder of the power being supplied by the battery. The power management algorithm used for this system is shown in Fig. 4.

3 Simulation result and Discussion

The Federal Urban Driving Schedule (FUDS) (see Fig. 5) and New European Driving Cycle (NEDC) (see Fig.6) were used as the basis for this simulation, which were run for around 1400s and 1200s, respectively. The power outputs of the motor for these two testing regimes are shown in Fig. 7 and Fig. 8, respectively. Use of the Federal Urban Driving Schedule (FUDS) schedule resulted in the vehicle consuming 124.2g of hydrogen using the fuel cell stack alone. When the vehicle was driven using the fuel cell stack and battery together (using the energy management model described above), the mass of hydrogen consumed was reduced to 105.7g (see Fig. 9). Therefore, use of the proposed energy management system resulted in an improvement in hydrogen consumption levels of 18.5g. Use of the New European Driving Cycle (NEDC) schedule, with and without hybridization, gave hydrogen consumption levels of 111g and 99g, respectively (Fig. 10). Therefore, both driving cycles gave improved fuel consumption, with the SOC of the battery showing improved recovery capacity (see Fig. 11~12), without the batteries lower or higher limits being exceeded.

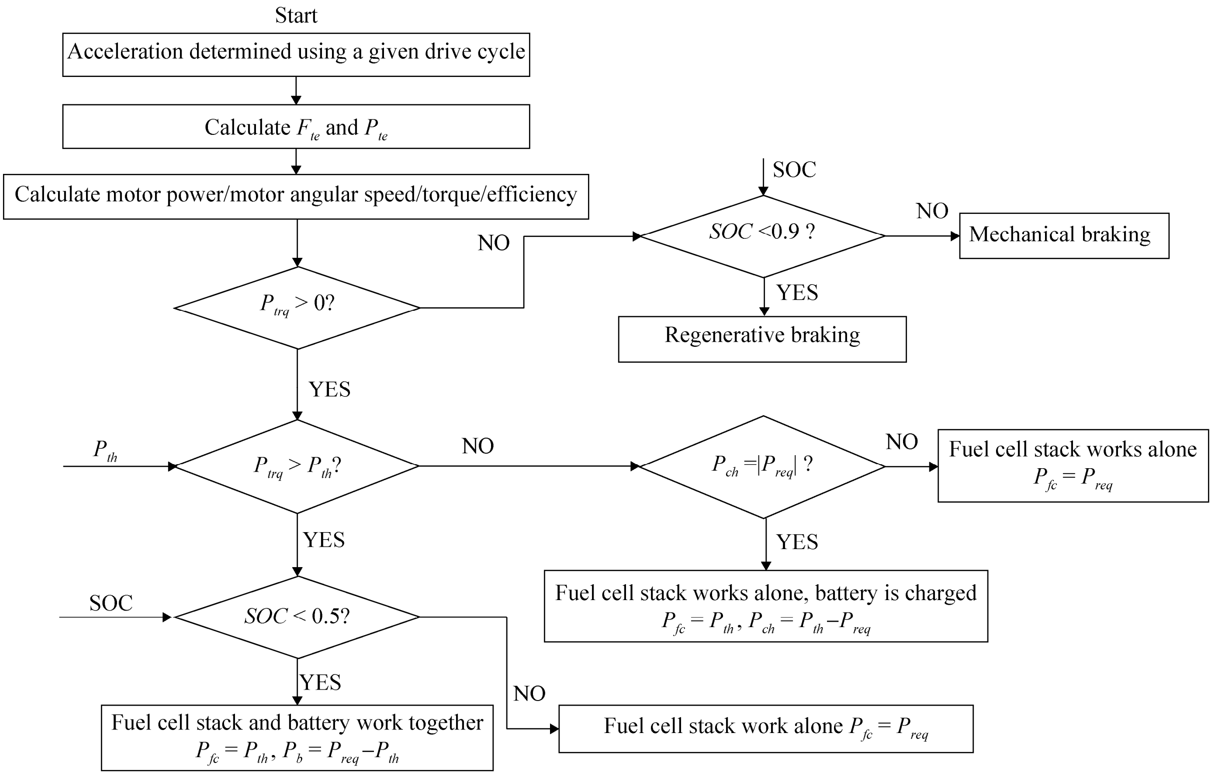

Fig. 4　Vehicle energy management flow-chart

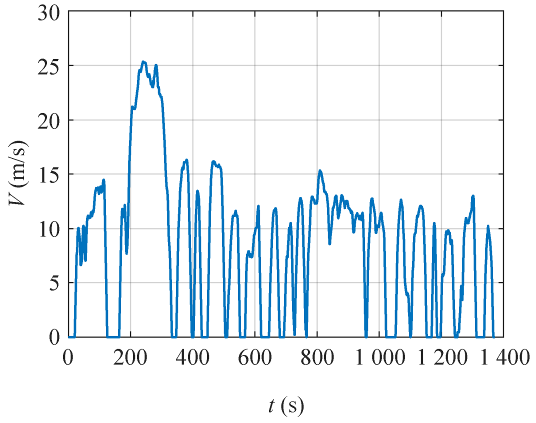

Fig. 5　The Federal Urban Driving Schedule (FUDS)

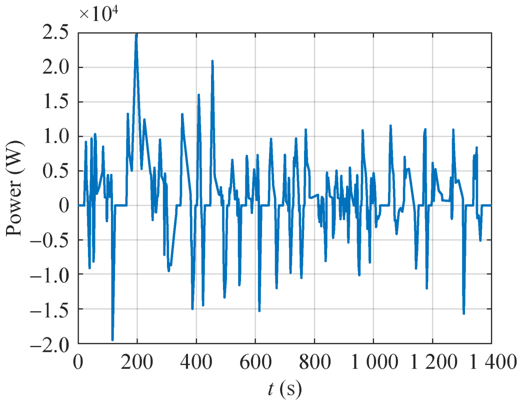

Fig. 7　Motor power (W) (FUDS)

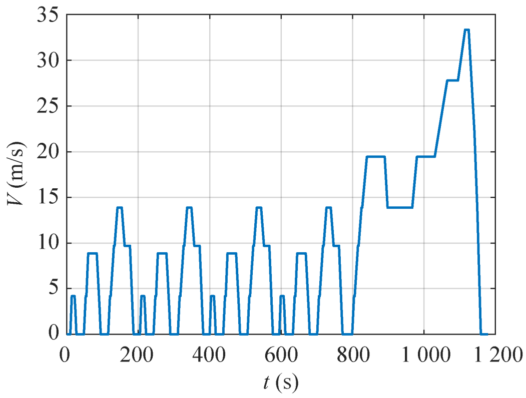

Fig. 6　New European Driving Cycle (NEDC)

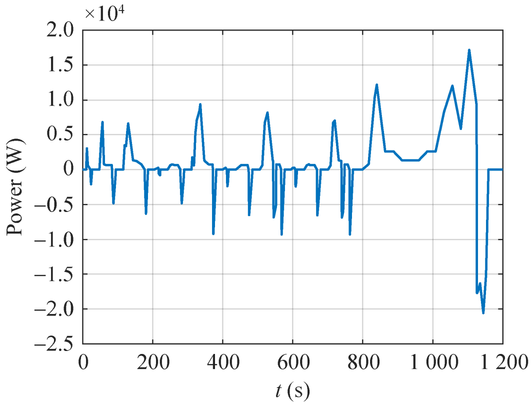

Fig. 8　Motor power (W) (NEDC)

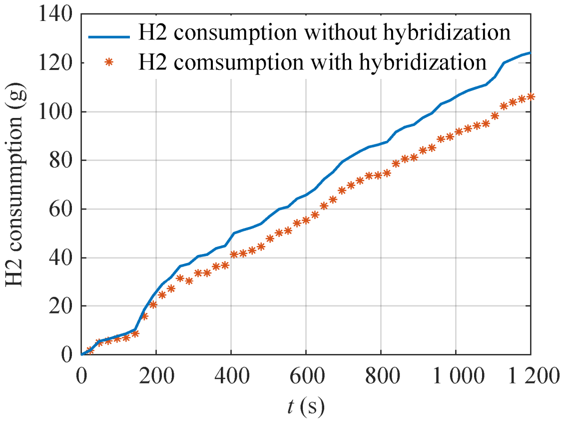

Fig. 9 Mass of hydrogen consumed, with and without hybridization (FUDS)

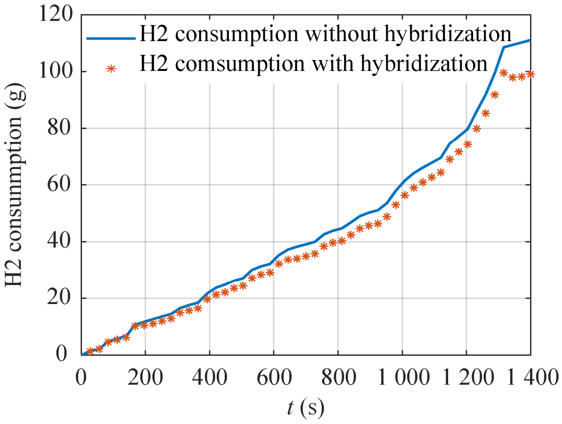

Fig. 10 Mass of hydrogen consumed, with and without hybridization (NEDC)

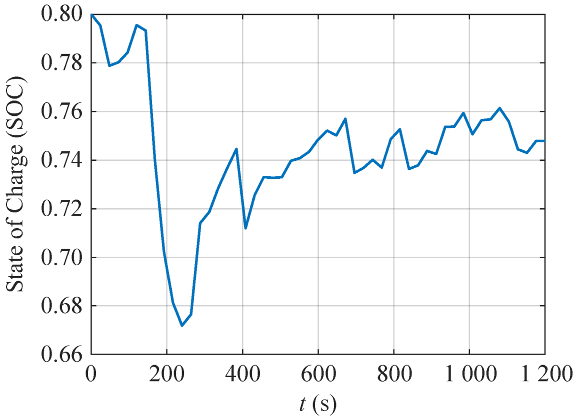

Fig. 11 State of charge of the battery (FUDS)

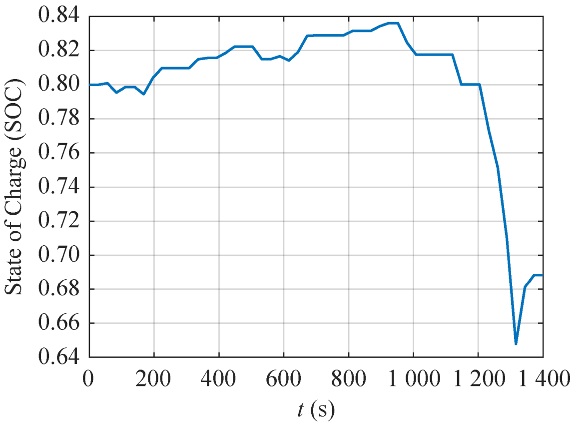

Fig. 12 State of charge of the battery (NEDC)

4 Conclusions

This paper describes a model of a fuel cell hybrid vehicle incorporating a PEM fuel cell, battery and a whole power train. Generative braking capacity has been included in this model, with a buck boost converter allowing for bidirectional energy flows that can rapidly increase power when the vehicle accelerates and absorb regenerative braking power to charge the battery when the vehicle decelerates. An energy management system has been developed based on the power threshold and the SOC of the battery system, with simulations using the FUDS and NEDC driving cycle revealing the possibility of improved hydrogen consumption and better recovery of battery SOC.

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