Journal of Zhejiang University SCIENCE A
ISSN 1009-3095 (Print); ISSN 1862-1775 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Simulation and analysis of energy optimization for PEMFC hybrid system*

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Received Oct. 21, 2005; revision accepted July 6, 2006

Abstract: The control objective and several key parameters of PEMFC hybrid system are analyzed. Control strategy design and energy optimization simulation are made individually for given cycle case and realtime operating case. For the given cycle case, genetic algorithm is adopted to solve the multi-constraint combinatorial optimization problem. Simulation result showed the algorithm's feasibility. As far as the realtime operation is concerned, based on the original fuzzy control strategy, the fuel cell voltage and voltage variance parameters are introduced to apply two-level modification on the fuzzy control output. The result reveals that the improved fuzzy control strategy can enhance the fuel cell efficiency and reduce the power fluctuations.

Key words: PEMFC, Hybrid system, Energy optimization, Fuzzy control
doi:10.1631/jzus.2006.A1878 **Document code:** A **CLC number:** TP29

INTRODUCTION

Proton Exchange Membrane Fuel Cell (PEMFC) is being rapidly developed in recent years because of its compact structure, light weight, low working temperature and rapid startup characteristics. But its E-I characteristic curve reveals its decreasing performance when confronted with suddenly increasing power demand, and high cost also restrains the application of the fuel cell. So the hybrid power scheme is the most suitable selection presently. Most of researches on fuel cell hybrid system abroad focus on the energy simulation and split power strategy of fuel cell/battery/super capacitors hybrid vehicles with ADVISOR and other simulation tools (Markel *et al*., 2002; Wipke *et al*., 2001; van Mierlo *et al*., 2004), while analysis on dynamic control response can seldom be done. Only Lee *et al*.(2003), Nasiri and Rimmalapudi (2004), and Iqbal (2003) conducted some simple tests on hybrid system control to obtain some experimental curves, but further analysis was not conducted. Some other researches considered the parameters including power demand and battery SOC (Lee *et al*., 2003; Gao and Ehsani, 2001), and some papers also allow stack voltage to be the fuzzy input, but without detailed description of the controller. As far as the research in China is concerned, analysis on the control strategy and optimization of fuel cell hybrid system has just started. As a whole, the systematic introduction of fuel cell hybrid control can seldom be seen in published documents.

With the low power PEMFC hybrid robot oriented, simulation of energy optimization and dynamic control strategy design was implemented.

CONTROL OBJECTIVE OF HYBRID SYSTEM AND KEY PARAMETERS

The control objectives are: (1) Minimize fuel usage; (2) Optimize hybrid system efficiency; (3) Maintain battery state of charge (SOC) as constant as possible; (4) Improve operating performance.

The hybrid system is a complex nonlinear sys-

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* Project (No. 2003AA517020) supported by the Hi-Tech Research and Development Program (863) of China

tem, composed of many factors, such as operating point of fuel cell, charging and discharging characteristics, stack voltage, and so on, influencing the operating performance. In order to reduce fuel consumption and improve the efficiency, optimized systematic design is needed, and appropriate control method must be selected. The main parameters to be considered are listed as follows:

(1) Good efficiency area of PEMFC. The fuel cell system efficiency is shown as a function of the net power in Fig.1. To ensure the best efficiency during actual operation, the fuel cell net power should be maintained between the two powers $P_{\min}$ and $P_{\max}$.

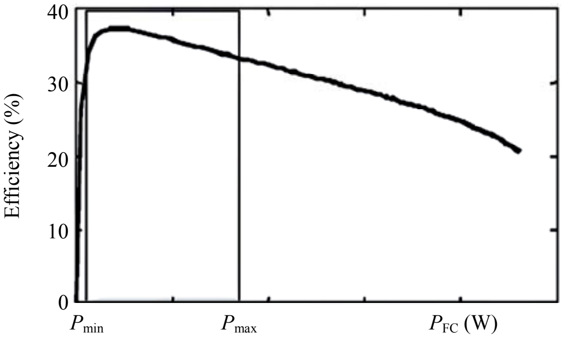

Fig.1 Efficiency map for stack power of fuel cell

(2) Stack voltage. The stack voltage must be kept within safe working range no matter what control methods are adopted. If the voltage is too low, the fuel cell must be cut off and the power demand is provided by battery alone.

(3) Load cycle requirement. When the power demand exceeds the preset value, the battery discharge circuit must be connected. The preset value can be adjusted according to the maximum fuel cell power available. At the same time, the power demand should be justified intelligently before being sent to the controller. When the power demand exceeds the power ability from the hybrid system, the power demand should be modified to the maximum available value.

(4) SOC. If SOC is lower than the preset bottom limit, the fuel cell should provide the charging power to the battery module. If SOC is higher than the top limit, the charging process should be stopped. Considering the battery charging and discharging efficiency, the SOC range is set to [0.3, 0.7] in this paper.

Energy optimization and control of hybrid system are simulated in this paper for given typical load cycle case and realtime operating case individually.

ENERGY OPTIMIZATION FOR GIVEN CYCLE CASE

Given the working cycle as reference, the power demand can be computed in advance. With the minimization of fuel consumption being the objective and other operating restraints, split dynamic power optimization can be solved.

Problem description

The hybrid system power structure is shown in Fig.2.

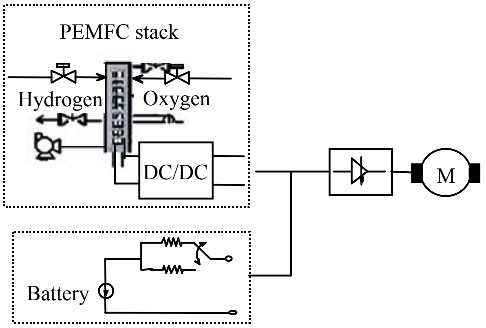

Fig.2 Power flow structure of hybrid powered system

From the power structure, we know the total power demand is:

$$P_{\mathrm{req}}(t)=P_{\mathrm{FC}}(t)+P_{\mathrm{batt}}(t), \tag{1}$$

where $P_{\mathrm{req}}(t)$ is the power demand during the cycle; $P_{\mathrm{FC}}(t)$ is the power provided by the PEMFC system; $P_{\mathrm{batt}}(t)$ is the power provided by the battery; The power demand can be further written as follows:

$$P_{\mathrm{req}}=P_{\mathrm{stack}}\eta_{\mathrm{dc}}+I_{\mathrm{batt}}(V_{\mathrm{batt}}-I_{\mathrm{batt}}R_{\mathrm{batt}}). \tag{2}$$

Hydrogen usage H during the cycle is:

$$H_{\mathrm{usage}}=\int_{t_0}^{t_1} bI_{\mathrm{FC}}(t)/\eta(t)\mathrm{d}t, \tag{3}$$

where b is a constant and $b=2N_{\mathrm{cell}}/(2F)$; $I_{\mathrm{FC}}(t)$ is the output current value; $\eta(t)$ is the fuel cell running efficiency; N_{cell} is the number of cells in the stack; F=96485 C/mol, the charge of one mole of electron.

After discretization, the equation above can be written as follows:

$$H=\sum bI_{\text{FC}}T_{\text{s}}/\eta_{\text{FC}}, \tag{4}$$

where T_{s} is the discretization period. So minimizing the fuel usage solves the problem:

$$H=\min\{\sum bI_{\text{FC}}T_{\text{s}}/\eta_{\text{FC}}\}, \tag{5}$$

With the combination of Eq.(2) and Eq.(5), the optimization problem can be:

$$\min B=\min\{\sum bT_{\text{s}}(P_{\text{req}}-(V_{\text{batt}}-I_{\text{batt}}R)I_{\text{batt}})/\eta_{\text{FC}}\}, \tag{6}$$

where $B=HV_{\text{FC}}\eta_{\text{dc}}$. The objective of optimization is to find the expected battery current value on each sampling time according to the corresponding load power demand.

Let x_i be the battery current value at the ith sampling time, which can be written as: $x_i=I_{\text{batt}}|_{(t=iT_{\text{s}})}$. At the same time, the sum of battery current should be kept to near zero value to maintain the SOC constant through the given cycle. So the objective function is changed to:

$$\min B=\min\{\sum f(x_i)+(\sum x_i)^2\}, \tag{7}$$

where

$$f(x_i)=\begin{cases} func(x_i), & \text{if}\, func(x_i)>0; \\ 0, & \text{if}\, func(x_i)<0, \end{cases}$$

$$func(x_i)=bT_{\text{s}}(P_{\text{req}}-(V_{\text{batt}}-x_iR)x_i)/\eta_{\text{FC}}.$$

Considering that the actual battery current is restrained by the lower and higher limit related with the present SOC, the following restraints are added:

$$x_i\in[\min_{x1},\max_{x1}],\, func(I_{\text{batt}})\in[\min_{y1},\max_{y1}], \quad \text{when } (c_i<c_{\text{limit}});$$

$$x_i\in[\min_{x2},\max_{x2}],\, func(I_{\text{batt}})\in[\min_{y2},\max_{y2}], \quad \text{when } (c_i\geq c_{\text{limit}}),$$

where c_{limit} is the maximum power available from the PEMFC system; $\min_{x1}$, $\max_{x1}$ and $\min_{x2}$, $\max_{x2}$ are the restraints for battery current when the power demand is less/more than the fuel cell maximum power, with values being related with the SOC; $\min_{y1}$, $\max_{y1}$ and $\min_{y2}$, $\max_{y2}$ are the restraints for PEMFC power output under corresponding situation mentioned above.

The optimization equation shows that the problem is a multi-constraint combinatorial optimization one. Considering that the genetic algorithm is easy to use without demands such as continuity and differentiability, it is adopted in the paper. Bin Encode, Bin Crossover and non-uniform mutation are adopted in the optimization algorithm.

Typical load cycle

In this paper the application is assumed to be off-road autonomous robot. The off-road travel of vehicles was analyzed regarding the frequencies of vehicle velocity and turning radius by calculating the percentage of time each of the vehicle operated within a certain velocity or turning radius range (Haugen and Ayers, 2003). At the same time, with the combination of reference (Barili *et al.*, 1995), the typical velocity curve is proposed in the paper, as shown in Fig.3.

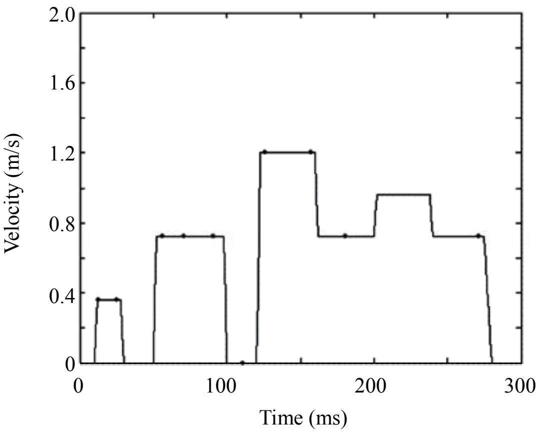

Fig.3 Curve of velocity expected

The points in Fig.3 mean turning movement at that time. The load cycle is a data package with self-defined function. According to the vehicle dynamics theory, the function computes the power demand with the road surface model and operating parameters such as velocity, acceleration and turning radius as the inputs. The power demand computed is shown in Fig.4.

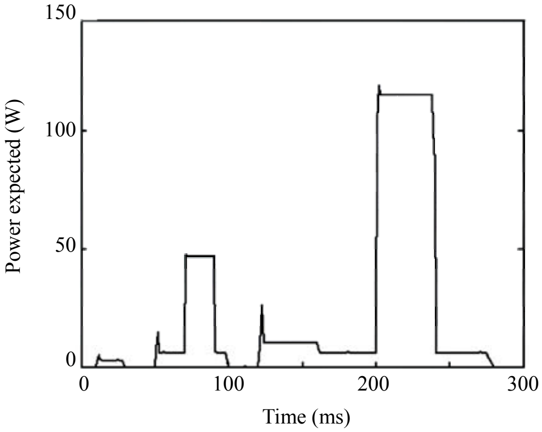

Fig.4 Curve of power expected

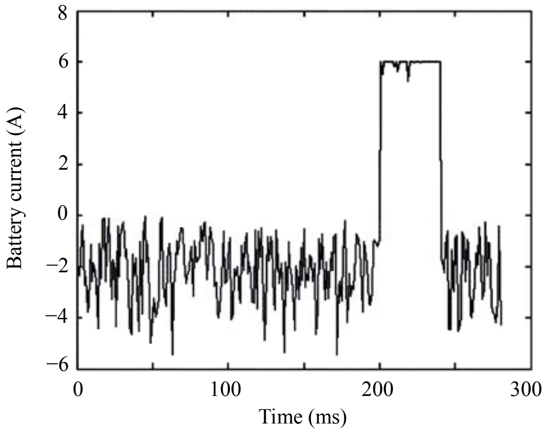

Fig.5 The optimized current value with the load model given

Simulation result

The optimized battery current curve for the given cycle case is shown in Fig.5. The expected fuel cell power output is shown in Fig.6, showing that the main power is provided by the PEMFC system when the power demand is less than 60 W, with the fuel cell providing the battery charging power. When the power demand exceeds 60 W, the battery provides the auxiliary power. The fuel cell output power is mostly maintained under 60 W, ensuring good efficiency during the working cycle. The simulation result showed that the algorithm is feasible.

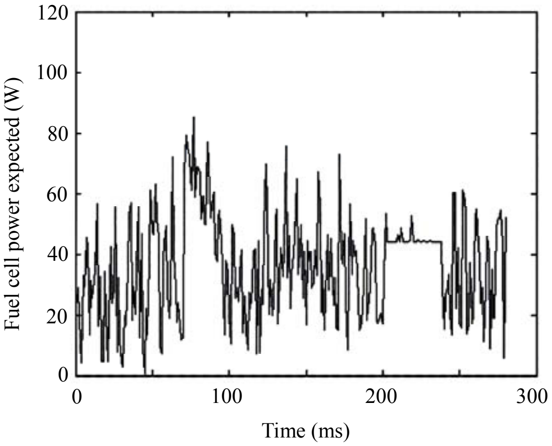

Fig.6 Stack power expected with the load model given

FUZZY CONTROL SCHEMES FOR REALTIME OPERATION

The fuel cell operating point is set according to the road surface load and battery SOC. Because the surface condition is complex and time-variant, appropriate control strategy must be designed to obtain realtime response under various possible conditions.

Design principle of control strategy

The objective is to realize split power control under various road surface conditions, then satisfy working performance requirement, achieve good economy, and ensure the fuel cell efficiency. Because of the existence of high nonlinearity, fuzzy control strategy is adopted in this paper. The main principles for designing the fuzzy rules are listed as follows: (1) Maintain the PEMFC power output at the preset range; (2) First consider the situation that stack voltage is decreased dramatically; (3) Decrease the fluctuation of PEMFC power output; (4) Decrease the fuel consumption; (5) Maintain the battery SOC at the preset range; (6) Stack voltage should not be reduced to lower than the bottom limit; (7) Modification for fuzzy rules is needed under different operating modes.

Fuzzy control strategy

Based on the considerations mentioned above, multi-input variant structure fuzzy controller was designed. First, the operating mode is determined according to the operating status data, and then fuzzy rules are chosen to satisfy the actual requirement. The fuzzy rule descriptions for different operating modes are listed as follows:

(1) Startup. Because it needs time to preheat for PEMFC startup, the power is provided by battery for startup mode. When the stack voltage increases to

higher than the rated value, the power supply is switched to fuel cell.

(2) Acceleration. If the power demand is more than the maximum PEMFC power, the fuel cell power can be kept as that of the last sampling time and the remaining power for the battery, or the fuel cell outputs the maximum power and the remaining power for the battery. The power split strategy depends on the battery SOC and stack voltage. Because the time for acceleration is rather short, short-time overload for PEMFC can be allowed.

(3) Cruising. The power demand is rather small for constant velocity operation under flat surface road condition. If the power demand is less than the PEMFC maximum power, the fuel cell supplies the whole power. Whether the battery is charged or not is determined by the SOC and power demand.

(4) Deceleration. When the power demand nears the zero value, the fuel cell is operated round the minimum power point, and charges the battery according to the battery SOC.

In addition to the power demand and battery SOC, the stack voltage and voltage variance parameters are also relatively important. The four parameters are introduced as the fuzzy inputs to provide more dynamic information and accurate basis for fuzzy decision, and the fuzzy output is the battery current expected. Then the PEMFC power expected can be obtained. To avoid the situation that power demand exceeds the system ability, the justification section is added before the fuzzy controller. The smaller one between power demand and hybrid maximum power available is defined as the power reference and connected to the fuzzy input. The fuzzy controller structure is shown in Fig.7.

The process can be briefly described: fuzzy reasoning is made with current power demand and battery SOC. The fuzzy output is modified by the two levels' modification of stack voltage and voltage variance parameters, and then is fed to the battery controller. The PEMFC power expected is also calculated.

Fuzzy control parameters

Power demand, battery SOC, stack voltage and voltage variance are chosen as the fuzzy inputs, and the output is the battery reference current. The range of power demand is set to [0, 150], and the ZO point corresponds to the maximum fuel cell power available. The voltage range is set to [8, 12]. The voltage variance range can be optimized from the simulation process, which is set to [−1.2, 1.2] in this paper. Considering the power demand and SOC parameters are the main factors determining the fuzzy output, the corresponding inputs are classified into 9 groups. Regarding the stack voltage variance, it is assumed that the fuzzy output is only influenced by the dramatic increasing and decreasing situation, so this input value is only leveled for PS and NS. The subjection functions are shown in Fig.8.

Design of control rules

Variant fuzzy control strategy is adopted in this paper. First, the operating mode is justified, and then different rules are utilized. Several examples of the rules are listed as follows.

The designing principles listed in Section 3.1 are mainly considered during fuzzy rules determination. In addition to this, the working mode and present stack maximum power available should also be

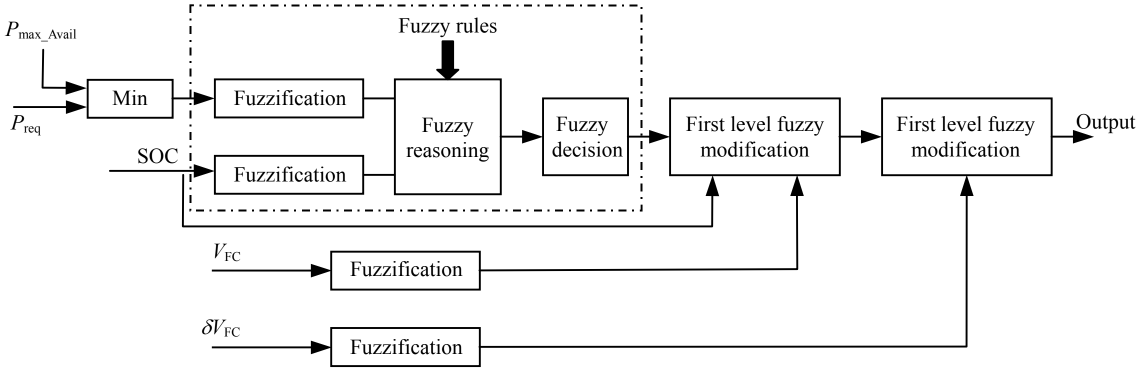

Fig.7 Sketch of fuzzy controller

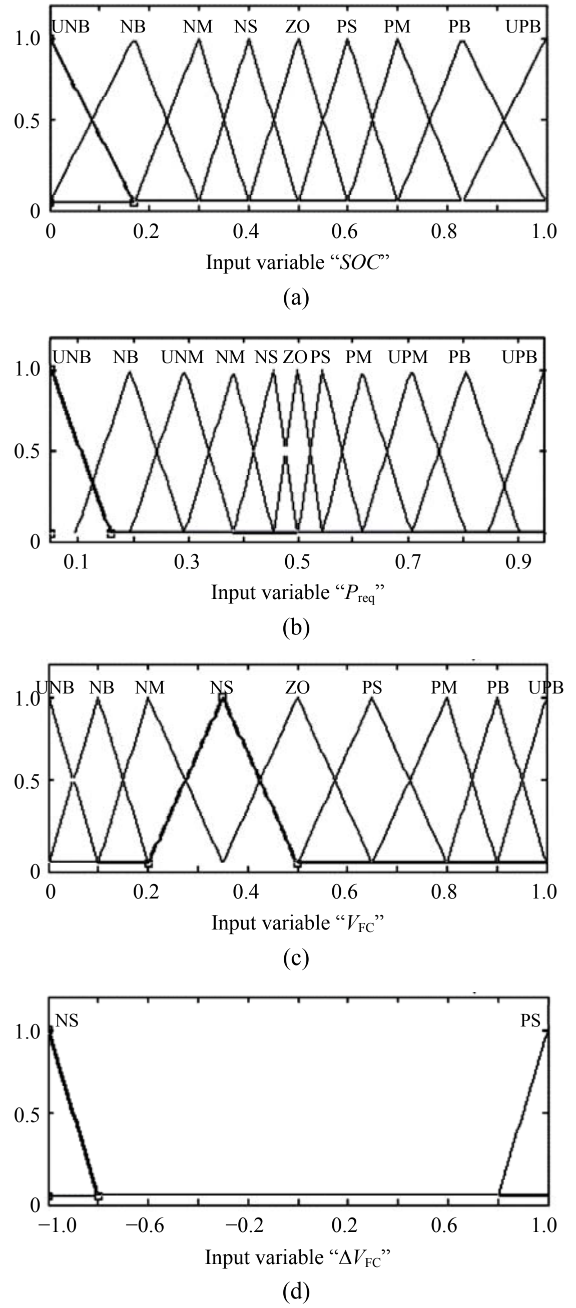

Fig.8 The subjection function of fuzzy variables. (a) Battery SOC; (b) Whole power requested; (c) Stack voltage; (d) Variance of stack voltage

taken into account. The working mode implements the intention of the robot body controller during motion planning, while exceeding the power ability should also be prevented. The rule designing under some situation is briefly described as follows:

(1) First, the split power strategy is determined by the power demand and battery SOC.

If P_{req} is NS and SOC is PM, the battery supplies the power demand. If the maximum available battery power is still lower than the demand, fuel cell current makes up for the difference.

If P_{req} is NS and SOC is NM, the power demand is set to the expected fuel cell power output. If the value is lower than the average running power, the difference is provided for battery charging.

(2) The present fuel cell voltage output should be taken into account based on the two parameters mentioned above.

If P_{req} is NS and SOC is NM and V_{FC} is PM, then a decrement can be added to the fuzzy output as the new expected current value for the battery. The decrement can be regarded as the charging power for the battery.

If P_{req} is NS and SOC is NM and V_{FC} is NM, an increment can be added to the fuzzy output. As a result, the battery power output is increased, and fuel cell power demand is reduced.

(3) The present voltage output can only reflect the steady performance. But the dynamic variance should also be taken into account. So the voltage variance is introduced.

If P_{req} is NS and SOC is NM and V_{FC} is PM and ΔV_{FC} is NS, it can be seen that the fuel cell power output is already near the maximum value. Then the new increment should be added on the first modification, and the new value is referred to as the expected battery current to avoid further deterioration of fuel cell performance. In addition, the total power available should be computed according to the current SOC, and then whether the power demand can be satisfied or not is determined.

If P_{req} is NS and SOC is NM and V_{FC} is PM and ΔV_{FC} is PS, the fuzzy output can be maintained or decrement is added as the final output. Then the fuel cell power demand is computed and sent to the fuel cell controller.

The corresponding rules are listed as follows:

If (P_{req} is NS) and (SOC is PM) then (I_{batt} is PM);

If (P_{req} is NS) and (SOC is NM) then (I_{batt} is NM);

First level modification:

If (P_{req} is NS) and (SOC is PM) and (V_{FC} is PM) then (ΔI_{batt_1} is NM);

If (P_{req} is NS) and (SOC is NM) and (V_{FC} is NM) then ($\Delta I_{\mathrm{batt\_1}}$ is PM);

Second level modification:

If (ΔV_{FC} is PS) then ($\Delta I_{\mathrm{batt\_2}}$ is NM);

If (ΔV_{FC} is NS) then ($\Delta I_{\mathrm{batt\_2}}$ is PM);

where, $\Delta I_{\mathrm{batt\_1}}$ and $\Delta I_{\mathrm{batt\_2}}$ are the two modifications of the fuzzy output.

Only part of the input cases is analyzed above and the others can be worked out in the same way.

The analysis showed that fuel cell power fluctuation can be reduced and that the fuel cell power ability can be kept from being exceeded.

Simulation result

For the simulation, the fuel cell maximum power was set to 60 W. To validate the feasibility of improved variant structure fuzzy control methods, the hybrid system is simulated with MATLAB program. The simulation result was compared with that of original fuzzy control strategy.

The power response curve with original fuzzy control is shown in Fig.9a. The power response curve after the stack voltage was introduced is shown in Fig.9b, showing presence of short-time overload, and that the power output is mainly less than 45 W. From the viewpoint of system efficiency, it is better than the original one. But the simulation curve reveals existence of fluctuations. So the voltage variance parameter is introduced to further modify the fuzzy output, the result is shown in Fig.9c.

Comparison shows that the overshoot is decreased, and that the dynamic response is more flat. The control algorithm has attained the expected effect.

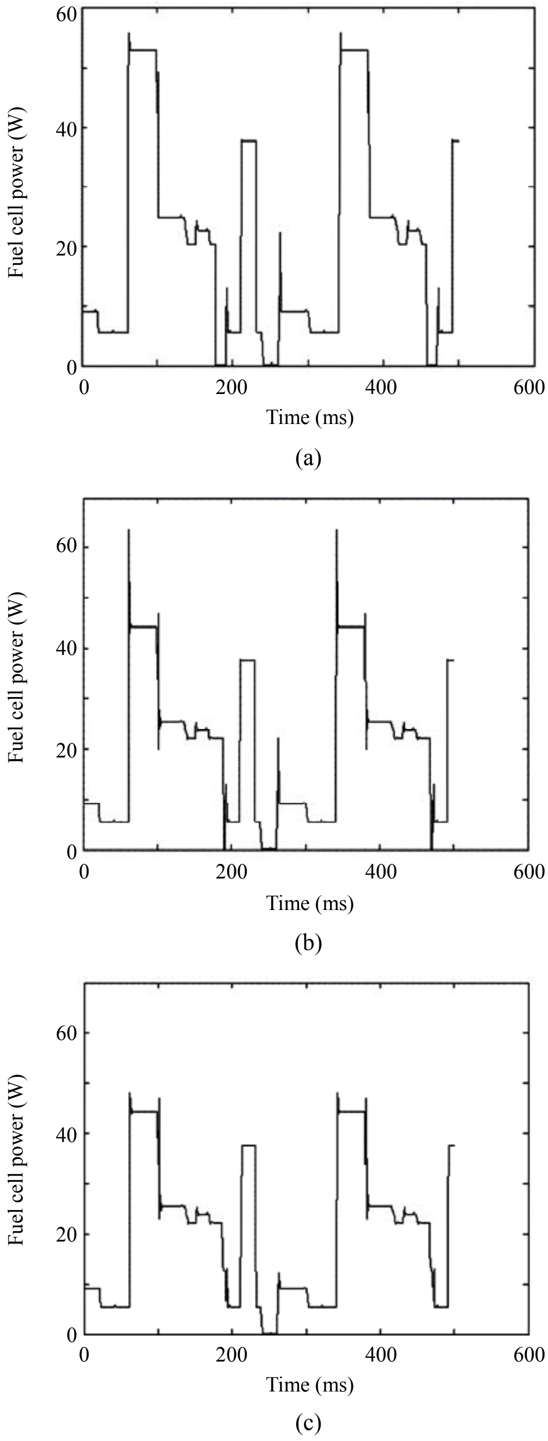

Fig.9 Stack power with the original strategy (a), voltage value introduced (b) and dual-modification (c)

CONCLUSION

Simulation and analysis were done for a given cycle case and realtime operation individually. For the given cycle case, to optimize efficiency and decrease fuel usage, a generic algorithm was adopted to determine the split power strategy. The simulation results indicated that the algorithm is feasible. For the realtime operation, stack voltage and voltage variance were introduced to make two level fuzzy modifications and realtime control was applied to the energy management of hybrid system. The simulation result showed that with the two parameters, system efficiency and economy can be improved and that the dynamic fluctuation can be reduced to some extent.

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