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An Energy Management Strategy for PEMFC Hybrid Vehicles based on Adaptive Model Predictive Control

Li Wang, Mince Li, Zhendong Sun, Zonghai Chen *
Department of Automation, University of Science and Technology of China, Hefei, China

ABSTRACT

Proton exchange membrane fuel cells(PEMFCs) have the advantages of clean efficiency, long range and fast recharging, with a short life span and harsh operating conditions. To ensure their safe operation, extend the life of PEMFCs and improve the dynamic characteristics of the power system. This paper uses a combination of PEMFC, battery and supercapacitor (SC) to form a PEMFC hybrid power system. A comprehensive dynamic model is developed for the non-linearity and time-varying nature of the system. Based on this, Adaptive Model Predictive Control (AMPC) is used to allocate power to the system. Minimized hydrogen consumption is considered in the rolling optimization function in AMPC. The simulation is validated by two different types of operating conditions and the experimental results show the effectiveness of the system's model and power allocation strategy. The proposed energy management strategy can improve the stability of the PEMFC output and guarantee that the fuel cell, battery and SC work in a safe interval.

Keywords: PEMFC, Battery, Supercapacitor, energy management, adaptive model predictive control

1. INTRODUCTION

Energy and environment are the basis for human survival and development[1]. However, it is an indisputable fact that the world's oil resources are getting depleted and the ecological environment is seriously deteriorating, which has seriously restricted sustainable economic and social development[2]. These are serious situations that countries around the world must assume. The fuel cell vehicle (FCV) can achieve zero pollution emission and high energy conversion efficiency with low noise and diversified energy sources. It can greatly alleviate environmental pollution in the transportation sector and is widely considered to be the ultimate goal of new energy vehicle development[3].

PEMFC is the most widely used fuel cell for vehicles [4]. As the dominant power source for fuel cell vehicles, PEMFC is receiving more and more attention for its advantages of good stability, high efficiency, and high specific power. However, fuel cells suffer from defects such as soft output characteristics and high- time hysteresis, which are not suitable for situations with rapid load changes. In order to compensate for these shortcomings, speed up the system start-up time and operating response time, improve the system energy utilization efficiency and extend the fuel cell life, the method of adding auxiliary energy can be implemented.

The power energy system with fuel cell as the main system and lithium battery/SC as the supplement has been widely promoted and applied in new energy vehicles. Among them, the structures of fuel cell + lithium battery (FC+B) and fuel cell + SC (FC+SC) have been studied to some extent[5]. However, there are still many challenges in the application of fuel cell hybrid power system. For example, effective management of fuel cell, lithium battery and SC is needed; coordinating the power distribution of each energy source; giving full play to the advantages of each; maximizing the overall lifetime; minimizing fuel cost and energy loss, etc.

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Energy management strategy(EMS) is the most important part to distribute power for each energy source. Most of the research on EMS has focused on oil-electric hybrid vehicles. The transfer of these methods to fuel cell hybrid vehicles requires the prerequisite of an additional consideration of the behavioral characteristics of the fuel cell. In general, EMS can be divided into three categories: rule-based, and optimization-based. Rule-based methods are simple to control and have low initial costs[6], but usually require expert knowledge or known operating conditions as conditions, have coarse control boundaries and cannot achieve fine control[7].

The optimization-based energy management strategy starts from an optimization point of view and uses optimization methods to find the optimal solution to the objective function based on the actual demand for the actual system performance cost objective function, such as maximizing the fuel cell life, and then obtains the optimal system power allocation result. SI et al[7]. adopt an adaptive constrained differential evolutionary algorithm for the joint optimization of power allocation and capacity rationing. Li et al [8].applied a moth-flame optimization algorithm (MFO_PDU) based on location perturbation update strategy. One typical algorithm of this type is the model predictive control algorithm, which can be used to solve the non-linear, time-varying problems of the PEMFC hybrid model[11]. Li et al [9]presented an energy management strategy based on the Pontryagin's maximum principle (PMP) control strategy for power distribution between fuel cells and lithium batteries. Tang et al[10]. proposed an energy optimization management method with MPC as the main strategy and a rolling optimization function solved by the PMP algorithm. Wang et al [11]. proposed an energy management strategy based on adaptive model predictive control that incorporates system energy loss and battery current multiplier into the optimization objective expression, and the results show a 24.4% reduction in peak battery current compared to PI control.

In this paper, an adaptive model predictive control is employed for energy management in PEMFC, battery and SC system. The structure of system is designed for three energy source. The system model is derived for MPC control. An improved rolling horizon function is proposed for minimize energy consumption. The simulation is applied to prove the effective of proposed EMS.

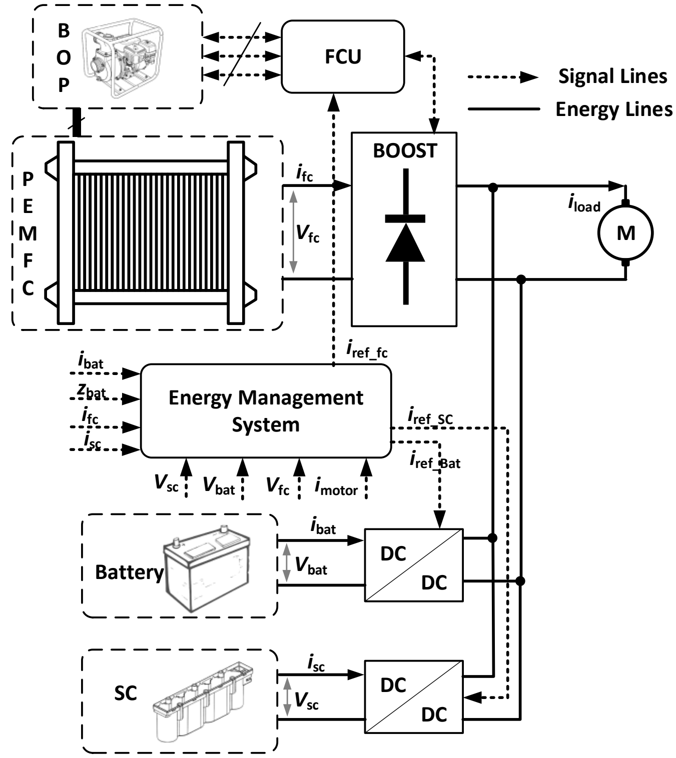

Fig. 1. Diagram of system topology

2. SYSTEM MODEL

2.1 PEMFC Model

The hydrogen consumption of the fuel cell system is expressed as follows.

$$\dot{m}_{h} = \frac{NM_{h_2}}{nF} i_{fc} \tag{1}$$

where M_{h_2} is the molar mass of hydrogen, n denotes the number of electrons transferred, N represents the number of cells, F denotes the Faraday constant

The net output power of the fuel cell system (P_{fc}) is obtained by subtracting the power output of the reactor and the power of the auxiliary system, which includes the air compressor, humidifier, cooler, etc. The efficiency of a fuel cell system is defined as the ratio of net power to the power produced by the hydrogen and is calculated as

$$\eta_{fc} = \frac{P_{fc}}{\dot{m}_{h} LHV} \tag{2}$$

Where, LHV denotes the low heating value of hydrogen (120 MJ·kg-1). From Fig.1, the highest power range for fuel cell efficiency is around 5-34kW, and the fuel cell operating point should be as close to this range as possible.

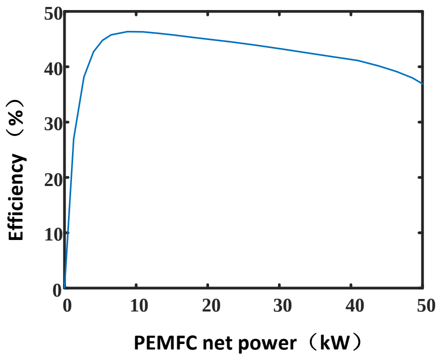

Fig. 2. PEMFC net power versus efficiency curve

2.2 Battery Model

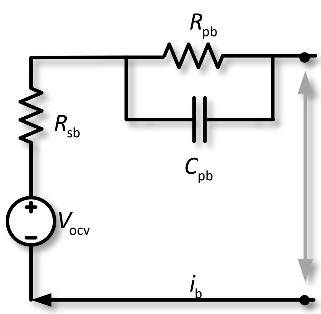

Fig. 3. Battery model

$$\begin{cases} C_{\mathrm{pb}} \cdot \dot{V}_{\mathrm{pb}} = i_{\mathrm{b}} - V_{\mathrm{pb}} / R_{\mathrm{pb}} \\ V_{\mathrm{b}} = m_{\mathrm{b}} \left(V_{\mathrm{ocv}} - V_{\mathrm{pb}} - i_{\mathrm{b}} R_{\mathrm{sb}} \right) \\ z_{\mathrm{b}} = z_{\mathrm{b}_0} - \int_{t_0}^{t} i_{\mathrm{b}}(\tau) d\tau / C_{\mathrm{Nb}} \end{cases} \tag{3}$$

Where, z_{b} is the SOC of battery. m_{b} is the series of battery. The battery pack is made up of 3.7V/10Ah cells and a first-order equivalent circuit model is developed for it, as shown in Fig.3.

2.3 SC Model

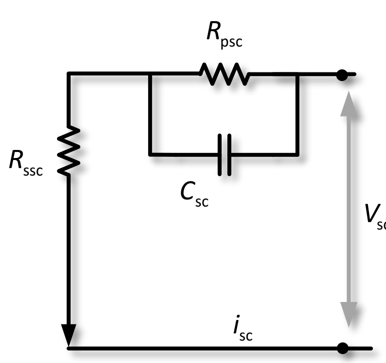

Fig.4. SC model

$$\begin{cases} C_{\mathrm{sc}} \cdot \dot{V}_{\mathrm{psc}} = i_{\mathrm{sc}} - V_{\mathrm{psc}} / R_{\mathrm{psc}} \\ V_{\mathrm{sc}} = m_{\mathrm{sc}} \left(V_{\mathrm{psc}} + i_{\mathrm{sc}} R_{\mathrm{ssc}} \right) \\ z_{\mathrm{sc}} = z_{\mathrm{sc}_0} - \int_{t_0}^{t} i_{\mathrm{sc}}(\tau) d\tau / C_{\mathrm{Nsc}} \end{cases} \tag{4}$$

The SC with a capacitance of 3000F and a voltage of 2.7V is selected. z_{sc} denotes the SOC of battery. m_{sc} is the series of SC.

3. ENERGY MANAGEMENT STRATEGY

3.1 Predictive model

From Figure 1, the power relationship between the PEMFC, the battery and the SC can be expressed as:

$$\eta_{\mathrm{boost}} P_{\mathrm{fc}} + \eta_{\mathrm{dc}} P_{\mathrm{b}} + \eta_{\mathrm{dc}} P_{\mathrm{sc}} = P_{\mathrm{load}} \tag{5}$$

$$\begin{cases} P_{\mathrm{sc}} = V_{\mathrm{sc}} i_{\mathrm{sc}} \\ P_{\mathrm{b}} = V_{\mathrm{b}} i_{\mathrm{b}} \\ P_{\mathrm{fc}} = a i_{\mathrm{fc}} \end{cases} \tag{6}$$

There is a linear relationship between fuel cell power and current [9]. The motor demand power is equivalent to the load power, which is given by the kinetic equation [11]. Therefore, the equation of state of the system can be obtained as (7).

3.2 Rolling horizon function

As the PEMFC hybrid system is strongly non-linear, time-varying, an adaptive model predictive control is applied for power allocation to PEMFC, battery and SC. Take equation (7) as the predictive model of AMPC. Rolling optimization is an important part of model predictive control and equation (8) is the objective function for rolling optimization. In this case, the first term considers the minimized hydrogen consumption. The reference values in items 2, 3 and 4 are the battery reference SOC, the SC reference SOC, and the FC reference operating power, respectively. z_{bref} , z_{scref} are set to 0.7 and 0.5. i_{fcref} is set to the corresponding current when the power value is at 10kw in HWFET, 5kw in UDDS.

$$\begin{aligned} J = & \sum_{i=1}^{p} \omega_1 m_h^2 (i_{fc}(t)) + \sum_{i=1}^{p} \omega_2 [z_{\mathrm{bref}}(k+i|k) - z_{\mathrm{b}}(k+i|k)]^2 \\ & + \sum_{i=1}^{p} \omega_3 [z_{\mathrm{scref}}(k+i|k) - z_{sc}(k+i|k)]^2 \\ & + \sum_{i=1}^{p} \omega_4 [i_{\mathrm{fcref}}(k+i|k) - i_{\mathrm{fc}}(k+i|k)]^2 \end{aligned} \tag{8}$$

$$\begin{bmatrix} V_{pb}(k+1) \\ V_{ps}(k+1) \\ z_b(k+1) \\ z_{sc}(k+1) \\ P_{fc}(k+1) \end{bmatrix} = \begin{bmatrix} e^{-\Delta t/C_{pb}R_{pb}} & 0 & 0 & 0 & 0 \\ 0 & e^{-\Delta t/C_{psc}R_{psc}} & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} V_{pb}(k) \\ V_{ps}(k) \\ z_b(k) \\ z_{sc}(k) \\ P_{fc}(k) \end{bmatrix} + \begin{bmatrix} (1-e^{-\Delta t/C_{pb}R_{pb}})R_{pb} & 0 & 0 \\ 0 & (1-e^{-\Delta t/C_{psc}R_{psc}})R_{psc} & 0 \\ \dfrac{-T}{3600C_{Nb}} & 0 & 0 \\ 0 & \dfrac{-T}{3600C_{Nsc}} & 0 \\ 0 & 0 & a \end{bmatrix} \begin{bmatrix} i_b \\ i_{sc} \\ i_{fc} \end{bmatrix} \tag{7}$$

$$st.\begin{cases} 0.2 \le z_b \le 0.8 \\ 0.1 \le z_{sc} \le 0.9 \\ 0 \le i_{fc} \le 150A \\ -n_{sc}\cdot 200 \le i_{sc} \le n_{sc}\cdot 200A \\ -n_b \cdot 30 \le i_b \le n_b \cdot 50 \end{cases} \tag{9}$$

Using the data sheets for fuel cells, batteries and SCs, the constraints are necessary in order for the system to work in a safe and efficient operating range. Where, n_b and n_{sc} represent the parallel of batteries and SCs.

4. SIMULATION

To demonstrate the effectiveness of the topology and power distribution strategy, two entirely different driving cycles were utilized: UDDS and HWFET, as shown in Fig5.

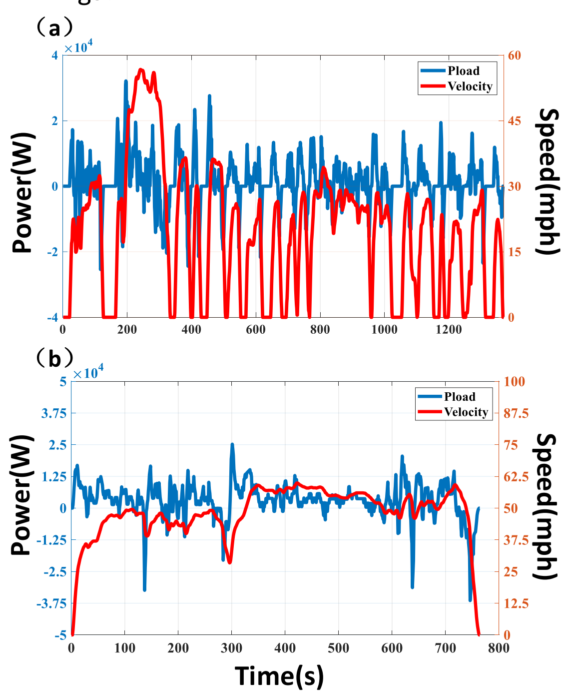

Fig.5. Driving conditions:(a) UDDS;(b)HWFET.

After the optimization by equation (8), the weights are adjusted so that several optimization objectives remain in the same order of magnitude. In this paper, the weighting is greater in order to guarantee the lifetime of the FC, its stable power output and its stability in the optimal reference operating interval.

Figure 6 shows the results of the power distribution strategy under UDDS operating conditions. It can be seen that the fuel cell is discharged at a constant power of around 5kw and the battery and SC provide fluctuating power. Where the Li-ion battery fluctuates less and the SC is responsible for high power charging and discharging. Similarly, in Figure 7, the fuel cell is at a constant output power of around 10kw, but due to the small power fluctuations in the early stages, the Li-ion battery charge and discharge power is small and basically the SC working alone can meet the working conditions.

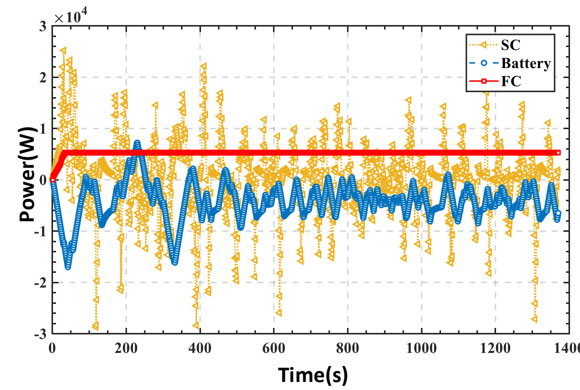

Fig.6. Power allocation results under UDDS

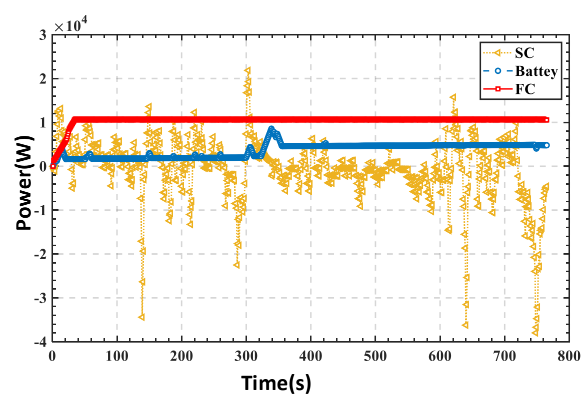

Fig.6. Power allocation results under HWFET

5. CONCLUSION

In this work, an integrated model of the three energy sources is developed for the strongly non-linear, time-varying PEMFC hybrid system and used in adaptive model predictive control. rolling optimization functions in AMPC are integrated to give guidance on safe operating intervals for the battery, SC and fuel cell, with minimization of hydrogen consumption as the main optimization objective. The proposed model and power allocation strategy are validated using two entirely different operating conditions. The experimental results demonstrate the validity of the model and the EMS based on the AMPC algorithm. This paper guarantees the stability of the hydrogen fuel cell operation and optimises the power dynamic characteristics of the PEMFC hybrid system. In future work, we will conduct further research on the capacity allocation of the system and implement the proposed strategy for validation in a real system.

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