Optimal Energy Management Strategy for a Light-Duty Fuel Cell Hybrid Electric Vehicle

Tianhong Wang [1)] Qi Li [1)] Weirong Chen [1)] Alexandre Ravey [2)] Elena Breaz [3)] Fei Gao [2)]

1) School of Electrical Engineering, Southwest Jiaotong University, Chengdu, China

2) FEMTO-ST Institute FCLAB, Univ. Bourgogne Franche-Comte, UTBM, CNRS, Belfort 90010, France

3) FEMTO-ST Institute FCLAB, Univ. Bourgogne Franche-Comte, UTBM, CNRS, Belfort 90010, France, and also with the Technical University of Cluj-Napoca, Cluj-Napoca 400604, Romania

E-mail: bk20121444@my.swjtu.edu.cn; liqi0800@163.com; wrchen@swjtu.edu.cn; alexandre.ravey@utbm.fr; elena.breaz@utbm.fr; fei.gao@utbm.fr;

ABSTRACT: High operating cost and low durability of stack are two main factors that limit the widespread commercial usage of fuel cell technology. Besides, most of the existing strategies focus only on ameliorating system operating efficiency or fuel consumption, but do not fully consider the impact of other factors such as power sources performance degradation. Based on above background, this study presents an optimal energy management strategy for a light duty fuel cell hybrid electric vehicle considering power sources durability and system operating cost. To achieve this purpose, this paper formulates a cost function that considers multiple factors such as the system total hydrogen consumption, power sources performance degradation degree and battery state of charge variation. In addition, sequential quadratic programming algorithm is used to solve the optimal reference power of the fuel cell. Furthermore, a global optimization-based dynamic programming algorithm will be used as the test benchmark in this study to evaluate the effect of the proposed strategy.

KEY WORDS: Fuel cell hybrid electric vehicle, battery, fuel cell, energy management strategy

1. INTRODUCTION

With the development of research on fuel cell hybrid electric vehicle (FCHEV), more and more studies focus on the research of energy management strategies (EMSs), such as power following (PF) strategy, dynamic programming (DP) algorithm and equivalent hydrogen consumption minimization strategy (ECMS). Although these strategies have achieved good results in some respects, most of the existing strategies only focus on minimizing fuel consumption [1]. In addition, most of the work regards fuel cell (FC) as static models with unchanged output characteristics, and does not consider the impact of stack performance degradation on the hybrid system [2].

Considering that the durability and the cost are two bottlenecks in the widespread use of FC technology in the energy market, thus, a new health-conscious EMS should be developed [3]. In addition, considering that the FC is a multi-physical system, and its operation performance is highly vulnerable to the working condition, the lifetime of the battery is also related to its output power. This causes a challenge of how to coordinate the output power of the two power sources, which can improve the overall operating economy of the vehicle.

Based on the above research background, the formulation principle of the EMSs in this study is to maximize the fuel utilization and extend the service life of the power sources under the premise of meeting the power demand of the system. This study mainly considers the optimization of the following factors:

1) Battery capacity degradation cost; 2) FC performance degradation cost; 3) Hydrogen consumption cost and equivalent hydrogen consumption cost; 4) The state-of-charge (SOC) variation of the battery.

After formulating the cost function, this study will use sequential quadratic programming (SQP) algorithm to solve the optimal value. The SQP algorithm is one of the common approaches for solving the constrained nonlinear optimization problems [4]. In addition, DP is a globally optimal benchmark, although it's computational efficiency is very low, especially for dynamic models with multiple states, this method can get the global optimal solution. Therefore, DP is often exploited to develop a theoretically optimum EMS and evaluate other algorithms. This study also adopt the DP as a comparison method to evaluate the performance of the presented method.

2. Fuel cell hybrid electric vehicle structure and components modeling

The research objective of this study is a 64 V FCHEV developed by Clean Energy Laboratory of Southwest Jiaotong University. The hybrid powertrain of this vehicle is composed by a FC and a battery. In order to facilitate the study of EMSs, it is first necessary to model each component of the FCHEV.

2.1. System structure and modeling

The appearance and basic structure of the vehicle employed in this study is depicted in Fig.1. It is a low-speed campus sightseeing vehicle that can carry 12 people. The battery is directly connected to the DC bus and is used as an energy storage system to hold the DC-link voltage and recover the braking power of the FCHEV. Besides, the FC is connected to a unidirectional boost DC/DC in series to supply the steady-state power for the vehicle.

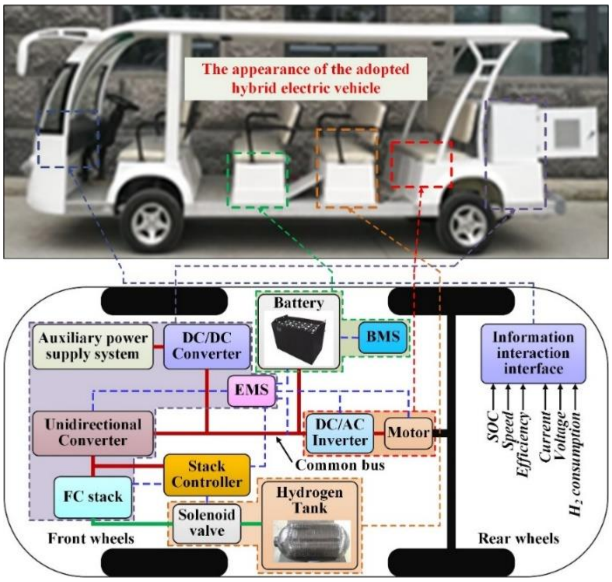

Fig. 1 Vehicle's appearance and structure.

The model of the vehicle powertrain can be represented by the following formula:

$$P_{\text{demand}} = \frac{P_{\text{t(v)}}}{\eta_{\text{drive}} \times \eta_{\text{DC/AC}} \times \eta_{\text{EM}}} = \frac{F_{\text{t(v)}} \times v}{\eta_{\text{drive}} \times \eta_{\text{DC/AC}} \times \eta_{\text{EM}}} = P_{\text{bat}} + P_{\text{FC}} \times \eta_{\text{DC/DC}} \tag{1}$$

where P_{demand} is the system demand power, $F_{\text{t(v)}}$ is generated by the torque applied by the motor to the wheels through the transmission system. η_{drive}, $\eta_{\text{DC/AC}}$, $\eta_{\text{DC/DC}}$, and η_{EM} respectively represent transmission system efficiency, inverter efficiency, the efficiency of the DC/DC converter, and the electric machine efficiency. v is the speed of the vehicle, while P_{bat} and P_{FC} are the output power of battery and FC, respectively.

The key components and parameters of this FCHEV are listed in Table 1.

Table 1 Primary components and parameters of the FCHEV.

FCHEV			
Bus voltage (V)	64	Max power (kW)	6
Size(cm^3)	520*149*208	Max speed (km*h^{-1})	30
FC			
Rated Power (kW)	3	Rated voltage (V)	43.2
Cell number	72	Rated current (A)	70
H_2 pressure (Bar)	0.45-0.55	Temperature (°C)	5-30
Battery			
Rated voltage (V)	3.2	Capacity (Ah)	20
Sustainable charge current (A)	60	Sustainable discharge current (A)	80

2.2. Fuel cell modeling

FC is a strongly coupled, multi-input electrochemical power generation device that can convert chemical energy into electrical energy. As one of the power sources in FCHEV, FC also needs to be modeled and analyzed. Usually a series of physical and chemical changes occur during the operation of the stack, and each process has a certain resistance. The output voltage loss caused by these resistances could be mainly divided into activation voltage loss, ohmic voltage loss, and concentration voltage loss. Therefore, the output voltage of the single cell could be expressed as:

$$U_{\text{cell}} = E_{\text{OC}} - U_{\text{act}} - U_{\text{ohmic}} - U_{\text{conc}} \tag{2}$$

where E_{OC} is the open circuit voltage, U_{act}, U_{ohmic}, and U_{conc} respectively represent activation voltage loss, ohmic voltage loss, and concentration voltage loss. The E_{oc}, U_{act}, U_{ohmic}, and U_{ocnc} can be further expressed as:

$$\begin{cases} E_{\text{OC}} = K_{\text{c}}\left(E^{0} + (T-298)\dfrac{\Delta S^{0}}{2F} + \dfrac{RT}{2F}\ln\left(P_{\text{H}_2}\sqrt{P_{\text{O}_2}}\right)\right) \\ U_{\text{act}} = \dfrac{1}{\tau_{\text{d}} s + 1} \times N_{\text{cell}} A \ln\left(\dfrac{I_{\text{FC}}}{i_0}\right) \\ U_{\text{ohmic}} = r_{\text{ohm}} I_{\text{FC}} \\ U_{\text{conc}} = \dfrac{RT}{NF} \times \ln\left(1 - \dfrac{I_{\text{FC}}}{i_{\max}}\right) \end{cases} \tag{3}$$

2.3. Battery modeling

Since the FC can't recover the braking power of the system, and the dynamic response capability is insufficient, the battery plays a very important role in the FCHEV. Based on the research of [5], the established battery model is as follows:

$$\begin{cases} SOC_0 = \dfrac{U_{\text{OCV}} - U_{\text{OCV\_1}}}{U_{\text{OCV\_1}} - U_{\text{OCV\_0}}} \\ SOC = SOC_0 - \dfrac{1}{Q}\displaystyle\int_0^{\text{T}} I_{\text{bat}}\, dt \end{cases} \tag{4}$$

where SOC_0 is the initial SOC value of the battery, U_{OCV} represents the open circuit voltage of the battery, $U_{\text{OCV\_1}}$ represents the open circuit voltage when the battery capacity is 100%, and $U_{\text{OCV\_0}}$ represents the open circuit voltage when the battery capacity is 0. I_{bat} is the output current of the battery.

2.4. DC/DC converter modeling

In order to provide stable electrical energy to the FCHEV, it is necessary to connect the FC to the DC bus port through a DC/DC converter. It can control the energy flow of the hybrid system by adjusting the output power of the converter, which is the basis for the realization of EMSs and other control algorithms. According to the power generation characteristics of the FC and the system structure, the converter topology we adopted in this study is shown in Fig. 2.

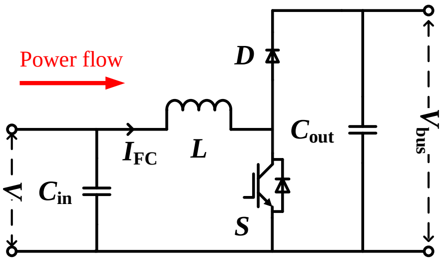

Fig. 2 Boost DC/DC converter topology.

3. The design of optimal system economic energy management strategy

The purpose of this work is to reduce the operating cost of the system and improve the durability of the stack. The main factors that affect the operating cost of the system include stack lifetime loss, hydrogen consumption, and battery charge-discharge depth. The following is a detailed analysis of these factors in order to formulate an objective function for evaluating the operating cost of the system.

Based on the research in [6], working conditions have a greater impact on the operating performance of the FC. The driving cycle is mainly composed of four conditions: start-stop, low power, high power, and load changing. The above factors will accelerate the degradation of stack performance, which is not conducive to maintaining the healthy and long-life operation of the stack. Therefore, this study formulates the functional relationship of the influence of output power on the lifetime of FC as follows:

$$D_{\text{FC\_loss}} = D_{\text{on/off}} + D_{\text{low}} + D_{\text{high}} + D_{\text{chg}} \tag{5}$$

here, $D_{\text{FC\_loss}}$ represents the performance degradation rate of FC. D_{low} is the performance degradation caused by FC in a low power operating state, which can be calculated by:

$$D_{\text{low}} = t_1' \times U_1' \tag{6}$$

where t_1' is the total operating time of the stack at low power and U_1' represents the degradation rate of the stack during low power operation. In addition, D_{high} is the lifetime loss during high power operation, which can be expressed by:

$$D_{\text{high}} = t_2' \times U_2' \tag{7}$$

where t_2' represents the total operating time of the stack at high power and U_2' is the degradation rate of the stack during high power operation. D_{chg} represents the degradation caused by the change of the output power of the stack, which can be expressed by:

$$D_{\text{chg}} = \frac{\sum_{i=1}^{n} \Delta P_{\text{FC,i}} \times U_3'}{N_{\text{FC}} \times D_{\text{FC}}} = \frac{\sum \left| P_{\text{FC}}\ t - P_{\text{FC}}\ t-1 \right| \times U_3'}{N_{\text{FC}} \times D_{\text{FC}}} \tag{8}$$

here, $\Delta P_{\text{FC,i}}$ is the fluctuation of the output power of the stack at the i-th moment, P_{FC}(t) represents the stack output power at the current moment, P_{FC}(t-1) represents FC output power at the previous moment, and U_3' represents the degradation rate of the stack when its output power changes. In addition, D_{FC} is the degradation rate of the stack. Considering that the output voltage can be used to indicate the operating state of the FC, the performance degradation degree of the FC can be defined as:

$$D_{\text{FC}} = 1 - \frac{\Delta U_{\text{rated}}}{\Delta U_{\text{rated,max}}} = 1 - \frac{U_{\text{rated,init}} - U_{\text{rated,degraded}}}{10\% \times U_{\text{rated,init}}} \tag{9}$$

where ΔU_{rated} is the stack voltage loss when the stack outputs the rated current under the current performance. $U_{\text{rate,init}}$ is the rated voltage when the stack has the best performance, $U_{\text{rated,degraded}}$ represents the voltage when the stack is outputting the rated current in the current performance state, and $\Delta U_{\text{rated,max}}$ is the maximum allowable voltage loss at rated current. According to the recommendations of the U.S. Department of Energy, this value is 10% of the rated voltage. Moreover, $D_{\text{on/off}}$ is the degradation of the stack caused by start and stop, which can be calculated by:

$$D_{\text{on/off}} = n \times U_4' \tag{10}$$

where n represents the number of start and stop of the stack during operation and U_4' is the degradation rate of the stack voltage caused by the start and stop actions. In addition to the degradation of stack operating performance, hydrogen consumption is another important factor affecting system cost. The total hydrogen consumption of the power sources can be calculated by:

$$C_{\text{sys}} = C_{\text{FC}} + C_{\text{bat}}\,. \tag{11}$$

In addition, the battery cycle life will be affected by the depth of charge and discharge. The formulated battery cycle life evaluation method is as follows:

$$D_{\text{bat\_loss}} = \frac{I_{\text{bat}} \Delta t}{Q_{\text{bat}} B_{\text{cycle}}} \tag{12}$$

where B_{cycle} is the total cycle life of the battery, which can be obtained from datasheet, and Δt is the sampling time

According to above description, using the FC lifetime loss evaluation formula and the battery capacity loss evaluation method, the lifetime loss of the power sources during system operation can be converted into operating costs. Then, considering the total hydrogen consumption, the system operating cost function can be formulated, as shown below:

$$J_{\text{total}} = \min\left(C_{\text{FC\_D}} + C_{\text{H}_2} + C_{\text{bat\_D}} + D_{\text{SOC}} \right) \tag{13}$$

with:

$$\begin{cases} C_{\mathrm{FC\_D}} = N_{\mathrm{FC}} \times \dfrac{D_{\mathrm{FC\_loss}}}{10\% \times U_{\mathrm{rated,init}}} \times P_{\mathrm{FC\_rated}} \times \beta_{\mathrm{FC}} \\ C_{\mathrm{H_2}} = M_{\mathrm{H_2}} \times \beta_{\mathrm{H_2}} \\ C_{\mathrm{bat\_D}} = \dfrac{\int_0^T D_{\mathrm{bat\_loss}} dt}{20\%} \times Q_{\mathrm{bat}} \times \beta_{\mathrm{bat}} \\ D_{\mathrm{SOC}} = D_{\mathrm{P}} \int_0^T \left(SOC - SOC_{\mathrm{init}} \right)^2 dt \end{cases} \tag{14}$$

where $P_{\mathrm{FC\_rated}}$ is the rated power of the adopted FC, β_{FC} is unit price of the stack, β_{H2} is unit price of the hydrogen, and β_{bat} is unit price of the battery. In addition, the function of the coefficient D_{P} is to restrict the fluctuation range of the battery SOC. The larger the value of D_{P}, the better the effect.

To ensure the safe and stable operation of the FCHEV, the equality and inequality constraints shown below are added.

$$\begin{cases} P_{\mathrm{FC\_min}} \le P_{\mathrm{FC}} \le P_{\mathrm{FC\_max}} \\ -D_{\mathrm{FC}} \Delta P_{\mathrm{FC}} \le \dfrac{dP_{\mathrm{FC}}}{dt} \le D_{\mathrm{FC}} \Delta P_{\mathrm{FC}} \\ P_{\mathrm{bat\_min}} \le P_{\mathrm{bat}} \le P_{\mathrm{bat\_max}} \\ P_{\mathrm{FC}} + P_{\mathrm{bat}} = P_{\mathrm{demand}} \end{cases} \tag{15}$$

where $P_{\mathrm{FC\_min}}$ and $P_{\mathrm{FC\_max}}$ are the minimum output power and maximum output power of the stack, respectively. In addition, ΔP_{FC} is used to limit the dynamic power fluctuations of the stack. Moreover, $P_{\mathrm{bat\_min}}$ and $P_{\mathrm{bat\_max}}$ are the minimum output power and maximum output power of the battery, respectively. The specific values of the above parameters are listed in Table 2.

Table 2. Parameters in the objective function

Parameter	Value
Low power operation	$U'_1 = 8.662\mu V/h$
High power operation	$U'_2 = 10\mu V/h$
Load changing	$U'_3 = 0.0441\mu V/\Delta kW$
Start-stop	$U'_4 = 13.79\mu V$

After formulating the evaluation function, the SQP algorithm is used to solve the optimal value of the objective function to obtain the minimum operating cost of the system.

4. Experimental test and conclusion

In order to test the performance of the presented strategy, this paper will carry out experimental verification on the hardware-in-the-loop simulation test platform shown in Fig. 3. On this platform, we will carry out experimental comparative analysis. We will mainly analyze the six indicators of battery SOC fluctuation range, system hydrogen consumption, FC operating efficiency, power sources operating stress, power sources lifetime degradation degree, and total system operating cost.

In the last part, we will summarize the research content of the paper and draw conclusions

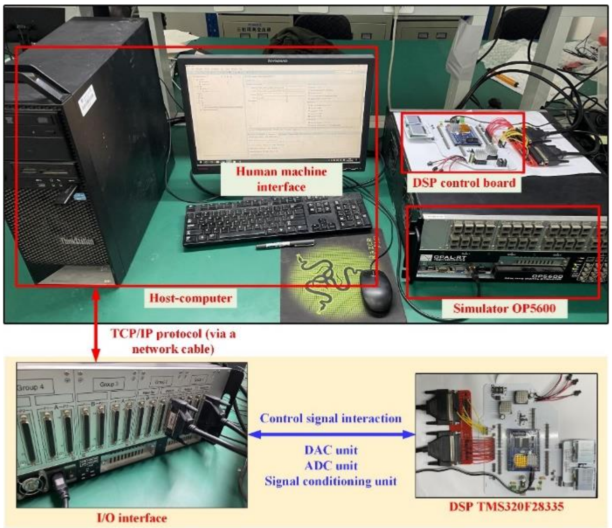

Fig. 3 Hardware-in-the-loop simulation test platform.

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