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Optimal fuzzy power control and management of fuel cell/battery hybrid vehicles

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ABSTRACT

Hybrid electric vehicles powered by fuel cells have been focused for alternative powertrains due to their high efficiency and low emission. The relative engine sizing and power split strategy of different power sources have great effect in influencing the fuel economy. In this paper, for a given driving cycle, the overall efficiency of a fuel cell/battery hybrid vehicle is maximized by identifying the best degree of hybridization (DOH) and a power control strategy. Fuzzy logic is used in power distribution of the hybrid vehicle, where the optimized centers and widths of membership functions are found by optimization. Simulation results show that the optimally designed and controlled hybrid vehicle can provide good fuel economy and overall system efficiency.

1. Introduction

The proton exchange membrane (PEM) fuel cell has the possibility of becoming the primary power source in vehicular applications due to its solid electrolyte, operating temperature and high power density [1]. However, the high cost and its slow dynamics are major obstacles for the commercialization of fuel cell electric vehicles (FCEVs). It is widely accepted that a single fuel cell electric system can't achieve performance similar to internal combustion engines. Other energy storage devices, such as batteries and supercapacitors, are needed to supplement the fuel cell in the FCEV powertrain to provide the required vehicle performance. Because of different characteristics of multiple power sources, the efficiency and the fuel economy of hybrid vehicles mainly depend on both the component sizing and power management strategy.

In recent years, many research works in the power distribution strategy of hybrid vehicles have been done. Some control algorithms for global optimization, based on a priori knowledge of a scheduled driving cycle, have been proposed in literature. Brahma et al. [2] used the dynamic programming technique in the optimization of instantaneous generation/storage power split in series hybrid electric vehicles. Delprat et al. [3] presented a global optimization method based on optimal control theory. Also, some real-time power management control strategies, based on a real-time optimization, are studied. Delprat et al. [4] derived a real-time control strategy from optimal control theory. Sciarretta et al. [5]. presented the equivalent consumption minimization strategy (ECMS), a real time control strategy which is not relying on the priori knowledge of the future driving conditions, to optimize the fuel used in a fuel cell/battery hybrid vehicle. Rodatz et al. [6] also used ECMS to determine the real time optimal power distribution of a fuel cell/supercapacitor hybrid vehicle.

The engine sizing is also a vital factor that influences the fuel economy and efficiency of hybrid vehicles. Wu and Gao [7] presented a design method to determine the component size that minimized the cost of the fuel cell and supercapacitor in a electric vehicle. Kim et al. [8] used fuzzy logic control in power management and proposed an optimal method based on well known city's driving cycle to design the relative power capacity between fuel cell and battery for a fuel cell/battery hybrid bus.

Furthermore, power management strategy and engine sizing are coupled together, which implies that different engine sizing should come with different power split strategy design. So these two should be determined as a combined package. Paladini et al. [9] focused on a car powered by a fuel cell with two secondary storage devices: batteries and supercapacitors. Engine size and parameters related with a power control strategy were determined to minimize the fuel consumption and the variation of battery state of charge by a multi-objective genetic algorithm (MOGA). Kim and Peng [10] designed a "pseudo-stochastic dynamic programming (SDP) controller" in power control and presented a combined power management and design optimization of FCHVs.

In this paper, a fuel cell/battery hybrid vehicle is studied and a fuzzy logic controller is used to manage the power distribution between the fuel cell and the battery. A optimal method based on the priori knowledge of driving schedule is proposed to design the

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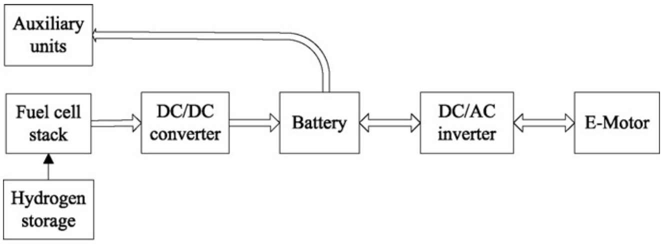

Fig. 1. Configuration of fuel cell hybrid vehicle.

degree of hybridization (DOH) and membership functions of the fuzzy controller. Consequently, the overall system efficiency based on simulation verifies the proposed optimal design method.

2. Fuel cell/battery hybrid vehicle model

The considered fuel cell/battery hybrid vehicle is configured as shown in Fig. 1. The vehicle is powered by a 75-kW AC motor with a maximum torque of 270 Nm. The fuel cell system (FCS) consists of the fuel cell stack, the DC/DC converter, fuel and air supplier and the management system of heat and water.

2.1. Fuel cell system model

The fuel cell applied to the hybrid vehicle is a proton exchange membrane fuel cell (PEMFC) and its current–voltage relation model is built, based on the test data. Fig. 2 shows the polarization curve of the fuel cell when the stack pressure is controlled at 130 Kpa. It is assumed that the temperature of the fuel cell system is well maintained at the operating condition (around 65 °C) and the pressure difference between the cathode and the anode is ignored. In this paper, the number of fuel cells is chosen as a design variable because it is easy to change the number of fuel cells. Theoretically, if the number of fuel cells is changed, the stack voltage will be changed because the cells are serially connected and consequently, the stack capacity is changed.

Power requirement of auxiliary components necessary to support the fuel cell system (FCS) should also be taken into account. It is found that auxiliary power can be up to 30% of the fuel cell stack power[1]. In this study, it is assumed that the maximal efficiency of FCS is 60%. The efficiency of the FCS strongly depends on the output power. A typical efficiency characteristic of a fuel cell system is shown in Fig. 3. Here, the efficiency is defined as the ratio between the net power produced and the heat of formation of the water produced if all the hydrogen feed is consumed [11]. The nominal power P_{FCnom} is 30 kW. When the FCS is operated at an output power rate less than 0.18, the efficiency is quite low and a significant gradient exists at low output power rate. To achieve good fuel economy, the FCS should be avoided to operate in this poor efficiency region.

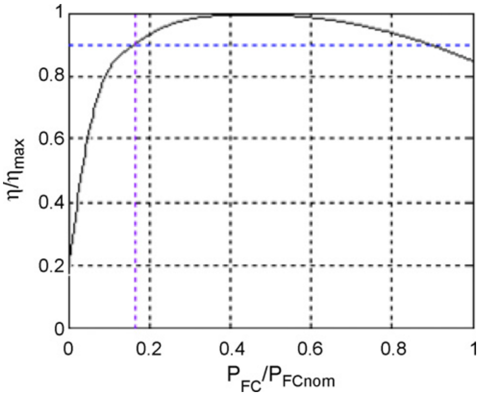

Fig. 3. Typical relationship between fuel cell efficiency and output power rates.

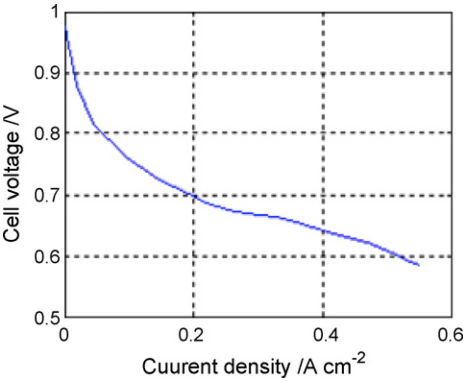

Fig. 2. Fuel cell polarization curve at a constant cathode pressure.

The hydrogen consumption of the fuel cell is calculated according to

$$M_{H_2} = \frac{1}{E_{low,H_2}} \int \frac{P_{fc}}{\eta_{fc}(P_{fc})} dt \tag{1}$$

where M_{H_2} is the hydrogen mass, E_{low,H_2} is the lower heating value of hydrogen, here, $E_{low,H_2} = 120\,\text{MJ}\,\text{kg}^{-1}$,$Pfc$ is the output power of fuel cell, η_{fc} is the efficiency of the fuel cell.

2.2. Battery model

Compared to supercapacitor, battery has the characteristics of high energy density and relatively low power density, but the power density of battery is still 3–5 times higher than that of a fuel cell system [12]. The internal resistance is the major factor to limit charging and discharging capability. The internal resistance model is used in this study. This model is related to work which was originally performed by Idaho National Engineering Laboratory to model flooded lead-acid batteries[13]. In the model, a battery is modelled with a voltage source and an internal resistor with temperature ignored (Fig. 4). The resistor has different values under charging and discharging conditions. As shown in Fig. 5, the resistance and open circuit voltage both are the nonlinear functions of battery state of charge (SOC). These relationships are implemented as look-up tables with test data. As shown in Fig. 4, the terminal voltage of battery pack V_b can be written by

$$V_b = n_b(V_{oc} - R_b I_b) \tag{2}$$

where n_b is the number of battery cells, V_{oc} is the open circuit voltage, R_b is the internal resistance and I_b is the current flow out the

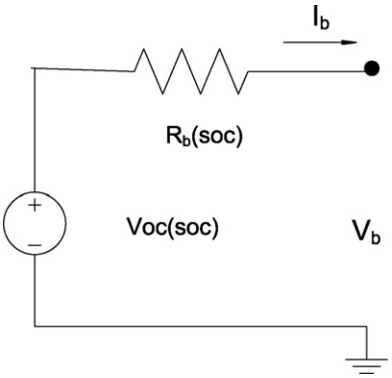

Fig. 4. Internal resistance battery model.

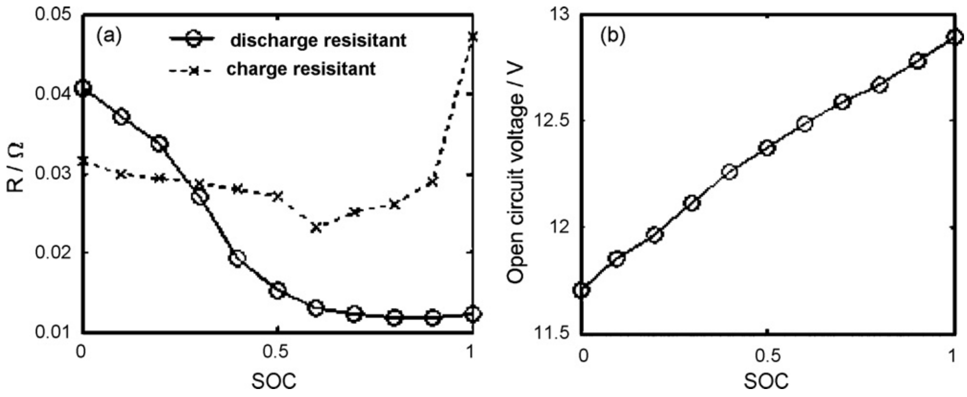

Fig. 5. The relationship between (a) internal resistance and SOC, and (b) open circuit voltage and SOC.

battery. If the battery pack is assumed to discharge some power P_b, then I_b can be calculated by

$$I_b = \frac{V_{oc} - \sqrt{V_{oc}^2 - (4R_b P_b / n_b)}}{2R_b} \tag{3}$$

where P_b is the battery power. If $P_b > 0$, it means the battery pack is discharging, the discharge efficiency of the battery pack can be written by

$$\eta_{dis} = \frac{(V_{oc} - R_{dis} I_b)}{V_{oc}} \tag{4}$$

Substitute Eq. (3) into Eq. (4), the η_{dis} is given by

$$\eta_{dis} = \frac{1}{2} + \frac{1}{2}\sqrt{1 - \frac{4R_{dis}P_b}{n_b V_{oc}^2}} \tag{5}$$

On the contrary, if $P_b < 0$, the battery pack is charging, the charge efficiency of the battery pack η_{chg} can be written as

$$\eta_{chg} = \left(\frac{1}{2} + \frac{1}{2}\sqrt{1 - \frac{4R_{chg}P_b}{n_b V_{oc}^2}}\right)^{-1} \tag{6}$$

where R_{dis} and R_{chg} are the discharge resistance and charge resistance of the battery cell.

The SOC of battery is denoted by

$$\mathrm{SOC}(k) = \mathrm{SOC}(0) - \frac{1}{C_b}\int_{t_0}^{t_k} I_b dt \tag{7}$$

where k is the time step and C_b is the capacity of battery cell. In the configuration of this hybrid vehicle, the battery pack is directly connected to the electric DC bus, so the terminal voltage of the battery pack should be kept in a certain range. Since changes in number of battery cells result in voltage changes of the DC bus, the number of battery cells is fixed and the battery cell capacity is taken as a design variable here.

2.3. DC/DC converter and DC/AC inverter

DC/DC converter is a device connected after fuel cell system to stable the fuel cell system voltage. Its efficiency ranges from 89 up to 96% with respect to the output power Fig. 6. In this paper, the DC/DC efficiency curve is scaled with respect to the fuel cell system nominal power [10]. The power flowing through the DC/DC converter and DC/AC inverter are therefore

$$P_{fc} = \frac{1}{\eta_{dc}(P_{DC})} P_{DC} \tag{8}$$

$$P_{tot} = \frac{1}{\eta_{ac}} P_m \tag{9}$$

where $\eta_{dc}(P_{DC})$ is the efficiency of the DC/DC converter, η_{ac} is the efficiency of the DC/AC inverter, P_{tot} is the total power that the DC bus delivered, P_m is the power of the AC motor. Here, $\eta_{ac} = 0.95$.

2.4. AC motor

The electric motor is the only source of propulsion power. So the motor size should be determined at the early stage according to the peak power requirements. In this paper, a 75-kW rated permanent

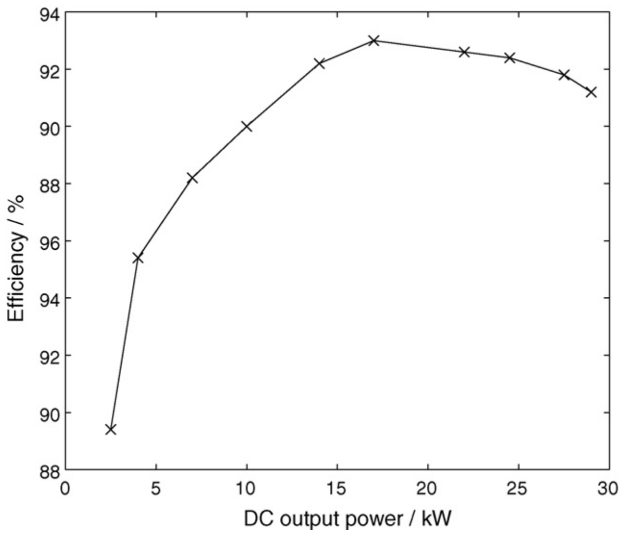

Fig. 6. DC/DC converter efficiency.

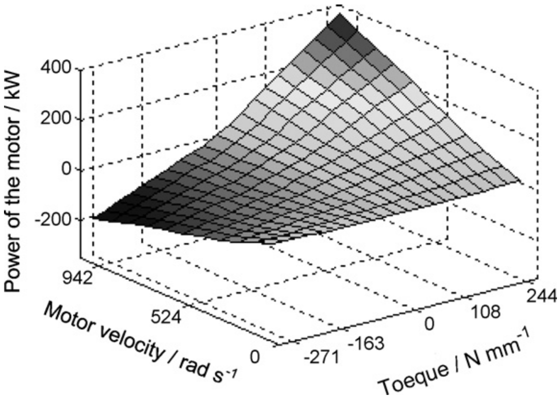

Fig. 7. Power map of AC motor

Fig. 8. Fuzzy logic controller for power split.

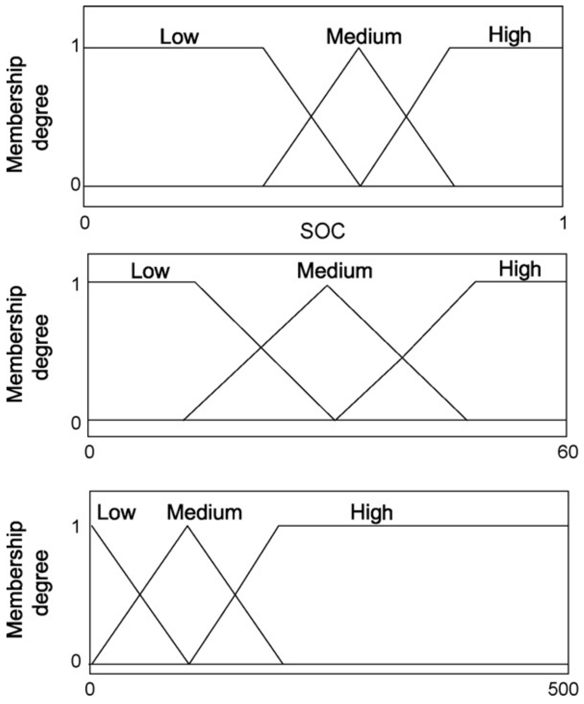

Fig. 9. Membership functions of fuzzy logic controller.

magnet synchronous ac motor is used. The power of AC motor is a function of electromechanical torque and motor speed

$$P_m = f(\tau_e, \omega) \tag{10}$$

The AC motor characteristic map is shown in Fig. 7. The power of motor is calibrated with this map.

3. Fuzzy logic power distribution strategy

The power management strategy should determines the split power between the fuel cell stack and battery while satisfying the load power requirement with respect to dynamic restrictions to the fuel cell stack and battery. Several studies developed fuzzy logic controllers to determine the power split between different power sources shown good fuel economy and system efficiency [14,15]. In this study, a fuzzy logic controller according to the load power demand and battery SOC is presented. Fig. 8 shows the fuzzy logic controller for power split.

The fuzzy logic controller is used to decide on the operating point of DC/DC converter. The power demand is the power of the vehicle required to drive. A fuzzy logic controller is a map from the controller inputs to outputs with a set of logic rules. In case of the low battery SOC, the DC/DC converter power is needed to be the high level to charge the battery fast. On the contrary, if the battery SOC is high, the DC/DC converter power should be kept at the low or medium level respective of the load power demand. Table 1 shows the rule base of the fuzzy logic controller. Triangular membership functions and center average defuzzification method are adopted. The membership functions are shown in Fig. 9.

4. Optimization problem formulation

This section describes the formulation of optimization problem. In Section 4.1, the design variables are chosen and their limits are determined. Section 4.2 explains the concept of equivalent fuel consumption. Section 4.3 is devoted to the optimization process and method. The final form of the optimization problem statement is shown in Section 4.4.

4.1. Variables designed in optimization

For hybrid vehicles, first, the maximum peak power to satisfy the vehicle drivability should be determined. From calculation, a total power of 60 kW is adequate to accelerate the fuel cell hybrid vehicle (the 1000-kg gross vehicle) from 0 to 60 mph in 10 s and maintain the vehicle at 100 mph top sustain speed. In the vehicle powertrain design, the DOH (degree of hybridization) should be determined then. The DOH is defined as the ratio of electric power can be delivered by the ESS storage (here it means the battery) to the total power that can be delivered by ESS and FCS [16]. Once a DOH is determined, both the number of fuel cells n_{fc} and battery cells capacity C_b are determined at the same time.

One goal of optimization is to find an optimal DOH between 0 and 1. If the DOH decreases, the capacity of battery cells will decrease and the number of fuel cells will increase. At this situation, the FCS can take the advantage of higher voltage, but the reduced capacity of battery may reduce the amount of regenerative energy due to power limits.

For the fuzzy logic power split strategy, the membership functions of the inputs (battery SOC and power demand) and output (DC/DC converter power) should be also determined by optimization. As explained in Section 3, the triangular memberships are used and the centers and widths of the membership functions are chosen by optimization. The design variables and their limits are shown in Table 2, where C_{soc} is the center point of the membership function of the input battery SOC, W_{soc} is the width of the membership function of the battery SOC, C_{Pd} is the center point of the membership function of the power demand, W_{Pd} is the width of the membership function of the power demand, C_{DC} is the center point of the membership function of the DC/DC converter power. Here, it is assumed that the width of membership function of the DC/DC converter power is equal to the value of its center.

Table 1
Fuzzy logic rules.

DC/DC power	Battery SOC		
	Low	Medium	High
Power demand			
Low	High	Low	Low
Medium	High	Medium	Low
High	High	High	Medium

Table 2
Design variables and their limits.

Design variables	Limits
DOH	[0 1]
C_{soc}	[0.4 0.8]
W_{soc}	[0.1 0.4]
C_{Pd}	[25 35]
W_{Pd}	[10 25]
C_{DC}	[10 30]

Table 3
Results of optimal design for driving cycles.

	Units	Lower bound	Upper bound	UDDS cycle		HWFETcycle		NEDC cycle	
				Power management design	Engine design only[a]	Power management design	Engine design only[a]	Power management design	Engine design only[a]
DOH	–	0.05	0.8	0.2985	0.4290	0.3602	0.3542	0.3417	0.4281
C_{soc}	–	0.5	0.7	0.5888	–	0.5918	–	0.5959	–
W_{soc}	–	0.1	0.4	0.2998	–	0.3864	–	0.2981	–
C_{Pd}	kW	25	35	26.63	–	26.17	–	26.30	–
W_{Pd}	kW	10	25	23.42	–	23.05	–	23.17	–
C_{DC}	kW	10	30	26.63	–	26.42	–	26.30	–
SOC_{max}	–	0.4	0.8	0.6262	0.6000	0.6308	0.6000	0.6261	0.6000
SOC_{min}	–	0.4	0.8	0.5991	0.5563	0.5998	0.5517	0.982	0.5324
ΔSOC	–	−0.03	0.03	0.0249	−0.0257	0.0299	−0.0234	0.0058	−0.030
max P_{fc}	kW	0	48	42.01	25.74	28.65	29.45	39.12	31.56
max ΔP_{fc}	kW	−10.67	10.67	8.418	5.148	7.678	7.749	7.900	6.863
Total H_2 consumption	g			142.6	161.9	154.5	164.4	123.1	140.8
Cycle length	km			11.99	11.99	16.51	16.51	10.94	10.94
Specific fuel consumption	g/km			11.89	13.50	9.358	9.958	11.25	12.87
MPGGE	–			54.54	48.02	69.29	65.11	57.64	50.38
FCS average efficiency	%			57.86	56.83	59.07	58.06	57.81	54.71
η_{hv}	%			27.75	24.44	41.94	39.41	31.58	27.62

[a] Fixed member functions, x = {DOH,0.6, 0.2, 30, 15, 15}.

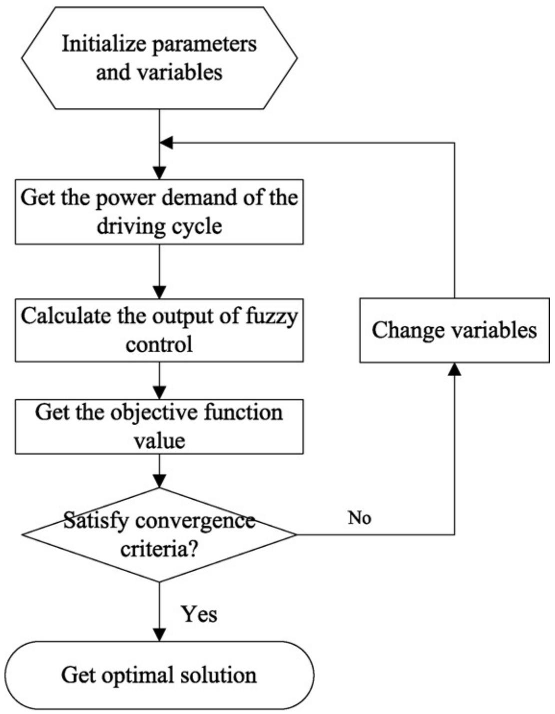

Fig. 10. Flowchart of design and power management optimization process.

4.2. The concept of equivalent fuel consumption

To make the electrical energy consumption of the battery and fuel energy of hydrogen comparable, the electrical energy consumption of the battery is converted into equivalent fuel consumption. Paganelli et al. [17] proposed the concept of equivalent fuel consumption, the average charge and discharge efficiencies are considered in this concept. The battery equivalent fuel consumption is defined as

$$C_b = \lambda_b P_b$$
$$\lambda_b = \begin{cases} \dfrac{C_{fc,avg}}{P_{fc,avg}\eta_{dis}\eta_{chg,avg}} & P_b \geq 0 \\ \dfrac{C_{fc,avg}\eta_{chg}\eta_{dis,avg}}{P_{fc,avg}} & P_b < 0 \end{cases} \tag{11}$$

where $C_{fc,avg}$ is the average fuel consumption of the fuel cell, $P_{fc,avg}$ is the average power of the fuel cell, η_{dis}, η_{chg} are, respectively, the discharge and charge efficiency of the battery, $\eta_{dis,avg}$, $\eta_{chg,avg}$ are respectively the average efficiency of discharge and charge given by Eqs. (5) and (6).

From Eq. (11), it can be see that if the battery discharged some power P_b, to maintain the SOC, the battery will be recharged using the energy of the fuel cell in the future. Because the future operating points are not known, the average charge efficiency of the battery is used and also, the average fuel cell power and its fuel consumption are used.

4.3. Optimization problem statement

The object of optimization problem is to maximize the efficiency of the fuel cell hybrid vehicle (Eq. (12)).

$$\eta_{hv} = \frac{\int_{cycle} P_{hv} dt}{E_{fc} + \int_{cycle} P_b dt} \tag{12}$$

where η_{hv} is the efficiency of the hybrid vehicle, P_{hv} is the power supplied in to the vehicle, E_{fc} is the energy of hydrogen fuel sup-

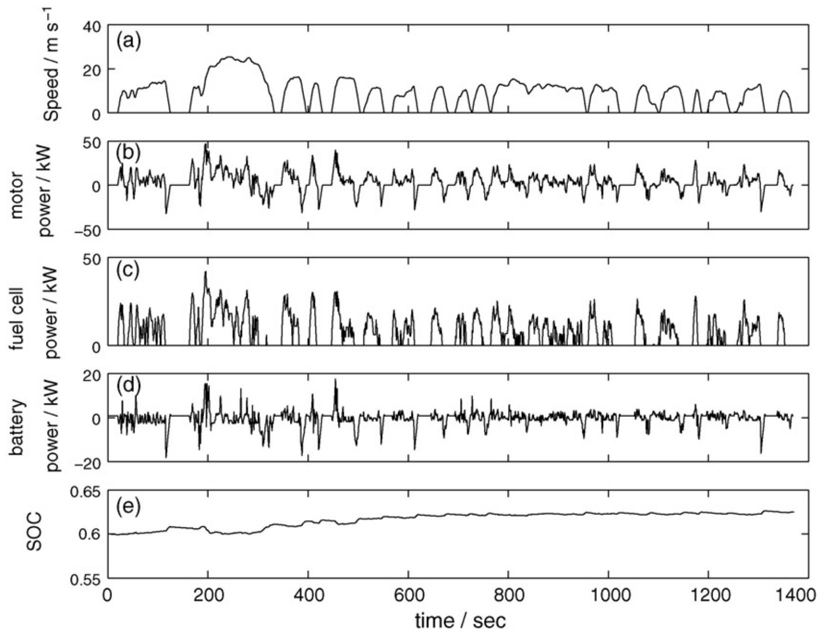

Fig. 11. Combined power management and engine sizing design results of UDDS cycle (a) vehicle speed, (b) total motor power, (c) fuel cell power, (d) battery power, and (e) battery SOC.

plied into the fuel cell stack, P_b is the battery power of charge or discharge.

The energy of hydrogen fuel supplied to the fuel cell is calculated according to

$$E_{fc} = \int_{cycle} \frac{P_{fc}}{\eta_{fc}(P_{fc})} dt \qquad (13)$$

The combined design and power management optimization problem can be expressed as follows:

$$\begin{aligned}
&\text{Maximize} : f(x) = \eta_{hv} \\
&\text{where} x = \{\text{DOH}, C_{soc}, W_{soc}, C_{Pd}, W_{Pd}, C_{DC}\} \\
&\max \text{SOC}(k) \le SOC_{max} \\
&\min \text{SOC}(k) \ge SOC_{min} \\
&s.t. \quad \Delta\text{SOC} \le 0.03 \\
&\max P_{fc}(k) \le P_{fcmax} \\
&\max \Delta P_{fc}(k) \le \Delta P_{fcmax}
\end{aligned} \qquad (14)$$

The difference between the initial and final SOC of time horizon ΔSOC is limited up to 3% to make sure that the battery doesn't need to be charged by other device. SOC$_{max}$ is the upper bound of SOC and SOC$_{min}$ is the lower bound of SOC. As a conservative target, 0.8 and 0.4 are used in this study. For the FCS, we use the static fuel cell model here and ignore the dynamic problems such as oxygen starvation or difference pressure between the cathode and anode. P_{fcmax} is the maximum power that can be delivered by the fuel cell. It is a function of DOH and the total power of hybrid vehicle. Take the slow dynamics of FCS into account, the net power rate of fuel cell ΔP_{fcmax} is limited to 6 kW s^{-1} with 30 kW rated power, which means the FCS will reach its maximum net power within 5 s.

4.4. Optimization method and process

The optimization problem is a nonlinear problem, also, it is hard to get a mathematical expression between the objective function and design variables. Gradient based optimization algorithms cannot be applied. In this paper, DIRECT algorithm [18] is used. It is very useful when the objective function is a "black-box" function. Fig. 10 shows the optimization process.

5. Optimization results and robustness

Table 3 summarizes the optimization results of the design variables and constraints for three driving cycles: UDDS, HWFET and NEDC. Here, "power management and design" means that both the DOH and parameters of membership functions are optimized whereas "engine design only" means only DOH is optimized with fixed membership functions. In this table, "MPGGE" means the miles per gallon gasoline equivalent.

Fig. 11 shows the simulation results with the optimized power management strategy and engine sizing design for UDDS cycle. The simulation results for HWFET cycle and NEDC cycle are shown in Figs. 12 and 13.

5.1. Results analysis

Among these three cycles, the UDDS cycle has the most accelerations and decelerations,as shown in Fig. 11. It is clear the hybrid vehicle will lose more energy. Therefore the overall hybrid vehicle efficiency of UDDS cycle is lowest. On the contrary, for the HWFET, the overall efficiency is highest because of near constant power demand and few accelerations and decelerations. Moreover, On the HWFET cycle, the fuel cell is more used than in other cycles. Due to lack of strong braking phases (Fig. 12), the battery does not have many chances to be recharged. This may explain why the DOH of HWFET is the lowest in these three cycles when only DOH is optimized. On the UDDS cycle, there exists a few of strong braking phases, so more battery cells are needed to collect the regenerative power, therefore, the DOH is highest in this cycle.

As shown by the results of Table 3, the parameters of membership functions of the fuzzy controller do not differ much among different driving cycles. This is very important because it implies that the fuzzy control power management strategy can be used in real time control.

From the simulation results of these three cycles (Figs. 11–13), it is worthy noting that the battery SOC of all the cycles does not

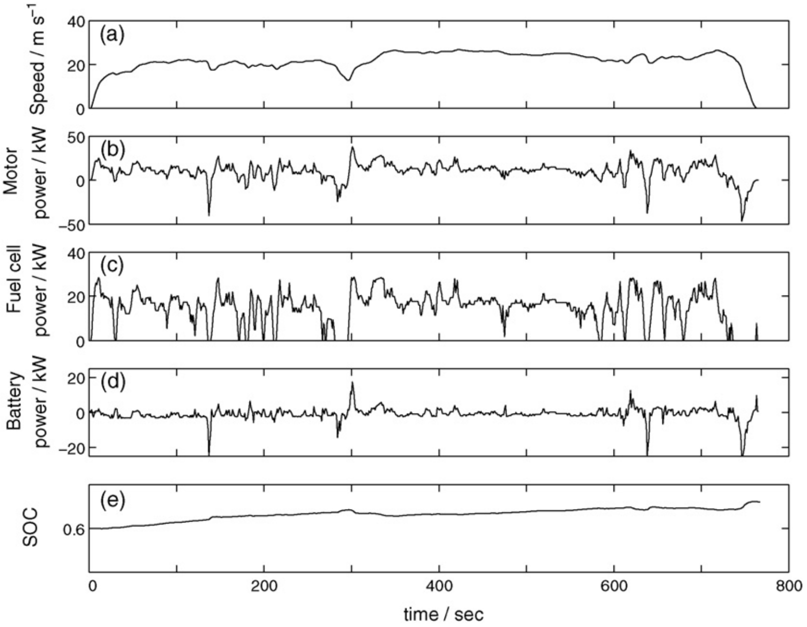

Fig. 12. Combined power management and engine sizing design results of HWFET cycle (a) vehicle speed, (b) total motor power, (c) fuel cell power, (d) battery power, and (e) battery SOC.

change much during the time horizon. This may increase the cost of the battery pack because the capacity of the battery is only small partly used. This problem is mainly depends on the battery characteristics. The discharge current of the battery is limited by the active materials of the battery cells and battery cell design. Because the number of battery cells is fixed to sustain the nominal voltage of the inverter side, so the capacity of battery should be increased to obtain a required battery power. The simulation results show that the battery SOC doesn't change a lot during the driving cycles, that means the battery capacity is not fully used. In addition, the constraint on the ΔSOC may aggravate this problem. But this situation will advantage the battery life. The small variation in SOC means that the depth of discharge (DoD) per cycle are significantly reduced and a lower DoD is good to achieve a longer battery life [19].

To verify the validation of the proposed fuzzy control power management and design optimization method, a similar test has been performed using a fuzzy control power management strategy with fixed membership functions. In this power management strategy, only DOH is optimized. The SOC corrected fuel efficiencies are given in Table 4 for three driving cycles. A 12.6% improvement is achieved on the NEDC, while just 6.03% is achieved on HWFET because there is not much room left for optimization since the power demand is nearly constant and relatively high. From the simulation results of these different power management strategies, it can be seen that the combined fuzzy control power management

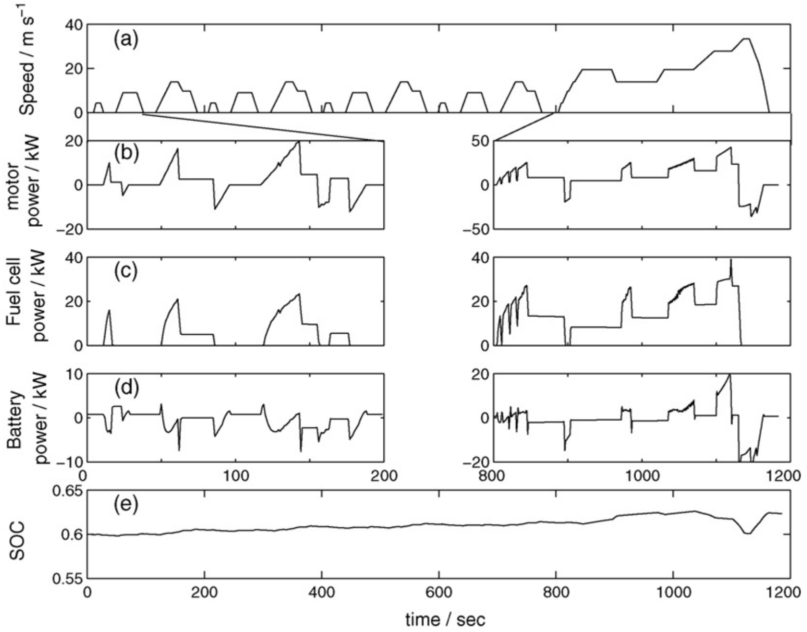

Fig. 13. Combined power management and engine sizing design results of NDEC cycle (a) vehicle speed, (b) total motor power, (c) fuel cell power, (d) battery power, and (e) battery SOC.

Table 4
Fuel efficiency improvement by optimization.

Power management strategy	Units	UDDS	HWFET	NEDC
Engine design only	g_{H_2} km^{-1}	13.50	9.958	12.87
Power managment and design	g_{H_2} km^{-1}	11.89	9.358	11.25
Improvement	%	11.9	6.03	12.6

and design optimization method can greatly improve the system efficiency.

Finally, in the worst case of the fuel cell hybrid vehicle, the MPGGE is 57. Compared with the combustion engine powered vehicle, assuming it requires 5 L of fuel per 100 km, the MPGGE of fuel cell vehicle is about 20% higher than the conventional vehicle.

5.2. *Statistical sensitivity analysis*

Once the optimum design and power management strategy are obtained using the optimization process described in Fig. 10, it is important to determine how sensitive is the optimization results to variation in values of model parameters (e.g. the battery internal resistance, the vehicle mass, driving cycle, etc.). Those values of parameters are associated with considerable uncertainty or changes along with their lifetime. To determine the robustness of the optimum design and power management strategy with respect to value variations in hybrid system parameters, Statistical sensitivity analysis will be used in this paper. Identify the factors that may effect the optimization results and their ranges of variation is the first step in statistical sensitivity analysis. This selection is subjective and depends on engineering experience. As the variation of vehicle mass only influence the power demand of driving cycle and different driving cycles have different power demands, so driving cycle is chosen as a factor. Kurisawa [20] made some efforts to connect the relationship between internal resistance and deterioration of the VRLA battery. In his research, the battery internal resistance will up to about 200% when it failed to maintain 80% of its rated capacity. Here, internal resistance of battery is selected as another factor. Each factor has threes levels which are listed in Table 5.

The next step is identify the analysis and quantify the effect of the selected factors. The optimization problem is solved with respect to three different levels of these two factors. The results are shown in Table 6. The values 1, 2 or 3 in this table correspond to the three levels of the corresponding factors defined in Table 5.

Table 5
Factors and levels used in statistical sensitivity analysis.

Factor	Units	Designation	Levels		
			1	2	3
Driving cycles	–	A	UDDS	NEDC	HWFET
Battery internal resistance	Ω	B	R_b	$1.5R_b$	$2R_b$

Table 6
The optimization results with respect to levels of factors.

Factors		C_{soc}	W_{soc}	C_{Pd}	W_{Pd}	C_{DC}	DOH
A	B						
1	1	0.5888	0.2998	26.63	23.42	26.56	0.2985
1	2	0.5980	0.2994	25.12	21.80	26.42	0.2985
1	3	0.5880	0.1998	25.53	22.96	23.32	0.3828
2	1	0.5959	0.2981	26.30	23.17	25.84	0.3417
2	2	0.5961	0.3776	26.82	23.66	26.23	0.2995
2	3	0.5885	0.2994	25.56	22.96	23.29	0.3880
3	1	0.5918	0.3846	26.17	23.05	26.42	0.3602
3	2	0.5819	0.3623	25.43	21.73	27.33	0.3231
3	3	0.5868	0.3944	25.56	21.85	26.91	0.3509

Table 7
Variance ratio *F* of two factors to the optimization results.

	C_{soc}	W_{soc}	C_{Pd}	W_{Pd}	C_{DC}	DOH
Internal resistance	0.67	0.10	$2.3\,e^{-4}$	0.21	1.39	0.60
Driving cycle	1.27	0.56	$1.0\,e^{-4}$	0.32	0.61	0.053

Then the statistical sensitivity analysis is carried out. The analysis of variance (ANOVA) is used to obtain the sensitivity of the optimum design and power management strategy to variations in the factors. The ANONA analysis procedure can be found in Ref. [21]. The outcome of ANONA analysis is variance ratio, *F*, for each factor. A value of *F* above four means that the optimization results are quite sensitive to the variations of the factor. Whereas a value of *F* that less than one suggests that the effect of the corresponding factor is statistically insignificant. The results of statistical sensitivity analysis are displayed in Table 7.

The results displayed in Table 7 show that the all the variance ratios are less than 1.4, just two out of these ratios are more than 1. This implies that those two factors have insignificant influence on the optimal design and power management strategy. Therefore, the optimal fuzzy power management strategy is robust despite some uncertainties in values of system parameters.

6. Conclusions

Although the proposed power management strategy and engine sizing design method needs a priori knowledge of driving cycle and is not suitable for real time control, it is still very necessary to improve the real system's efficiency and can be used as a basis to evaluate the quality of real time control strategies. In this paper, the fuzzy logic controller to manage the power split between the fuel cell and battery has been parameterized and some key parameters of the membership functions of fuzzy controller have also been included in design variables. With the use of DIRECT algorithm, the optimal values of parameterized fuzzy controller and engine sizing were found with respect to different driving cycles.

By simulation, the followings have been verified. Firstly, the optimized fuzzy control strategy can efficiently distribute the power between the fuel cell and battery. Secondly, there is no silver bullet solution for engine sizing that is suitable for all driving cycles. But the DOH does not differ much in different driving cycles and the sensitivity analysis implies that the driving cycle has insignificant effect on the optimal result of DOH. Finally, the fuzzy logic control strategy parameters are not sensitive to driving cycle and it can be expected to work well in the real driving conditions. In addition, both the battery model and fuel cell system model are based on lookup tables, so it is possible to take into account different battery types and various fuel cell power ranges with the proposed algorithm into account.

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