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Journal of Power Sources 178 (2008) 706–710

JOURNAL OF POWER SOURCES

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Short communication

Fuzzy control based engine sizing optimization for a fuel cell/battery hybrid mini-bus

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Received 10 October 2007; received in revised form 13 December 2007; accepted 13 December 2007
Available online 23 December 2007

Abstract

The fuel cell/battery hybrid vehicle has been focused for the alternative engine of the existing internal-combustion engine due to the following advantages of the fuel cell and the battery. Firstly, the fuel cell is highly efficient and eco-friendly. Secondly, the battery has the fast response for the changeable power demand. However, the competitive efficiency of the hybrid fuel cell vehicle is necessary to successfully alternate the conventional vehicles with the fuel cell hybrid vehicle. The most relevant factor which affects the overall efficiency of the hybrid fuel cell vehicle is the relative engine sizing between the fuel cell and the battery. Therefore the design method to optimize the engine sizing of the fuel cell hybrid vehicle has been proposed. The target system is the fuel cell/battery hybrid mini-bus and its power distribution is controlled based on the fuzzy logic. The optimal engine sizes are determined based on the simulator developed in this paper. The simulator includes the several models for the fuel cell, the battery, and the major balance of plants. After the engine sizing, the system efficiency and the stability of the power distribution are verified based on the well-known driving schedule. Consequently, the optimally designed mini-bus shows good performance.

Keywords: Engine sizing; Fuel cell hybrid vehicle; Mini-bus; Optimization; Fuzzy control

1. Introduction

The efficiency of the fuel cell/battery hybrid vehicle mainly depends on the relative engine size between the fuel cell and the battery. Generally, the fuel cell system (FCS) shows the poor performance when it is operated at too low or too high range of power. On the other hand, the battery shows that the loss of power arising from the charge or discharge according to the current state of charge (SOC) of the battery is changeable. Thus the overall system efficiency of the hybrid vehicle can be improved by making up for the weak points of the fuel cell and battery. To maximize the efficiency of the hybrid vehicle, the best engine sizing and the power distribution strategy are vital factors. The research works for the engine design and the control of the power distribution have been introduced [1–4]. Currently, the combined power management/design optimization techniques have been showed [5,6].

In this paper, we have proposed the optimal method to design the relative power capacity between the fuel cell and the battery for a fuel cell/battery hybrid mini-bus. The proposed method is based on the well-known city's driving schedule since the target system is the city tour mini-bus. In case of the power management, we use the fuzzy logic controller which can effectively control the changeable efficiency of both the fuel cell and the battery [1]. Consequently, the proposed design approach is verified based on the simulation in terms of the mini-bus efficiency and the stability of the power management.

2. Methods

2.1. Fuel cell/battery hybrid mini-bus

The target system is the city bus with the 25 seats. Its maximum speed is $70\,\mathrm{km\,h^{-1}}$ and the maximum power of the electric drive motor is 90 kW. Fig. 1 is the configuration of the target mini-bus system. The FCS consists of the fuel cell stack to generate the power, the DC/DC converter to amplify the power generated from the stack, the supplier of the fuel and air to the stack, and the management system of heat and water. The con-

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doi:10.1016/j.jpowsour.2007.12.047

Nomenclature

C_1	loss coefficient of the battery discharge
C_2	loss coefficient of the battery charge
CR	charge removed (kJ kg^{-1}, K)
C_p	specific heat of gas at constant pressure (kJ kg^{-1}, K)
DOD	depth of discharge
dt	sampling time (s)
E	open circuit voltage of battery (V)
F	molar flow rate (mole s^{-1})
f	relationship between DOD and R
I	current (A)
k	iteration number, $k = 1, 2, 3, \ldots$
LHV	lower heating value
n	number of electric batteries
P	power (W)
R	internal resistance (Ω)
SOC	battery state of charge
V	voltage (V)
η	efficiency

Subscripts

bat	battery
fc	fuel cell
fchv	fuel cell hybrid vehicle
H_2	hydrogen fuel

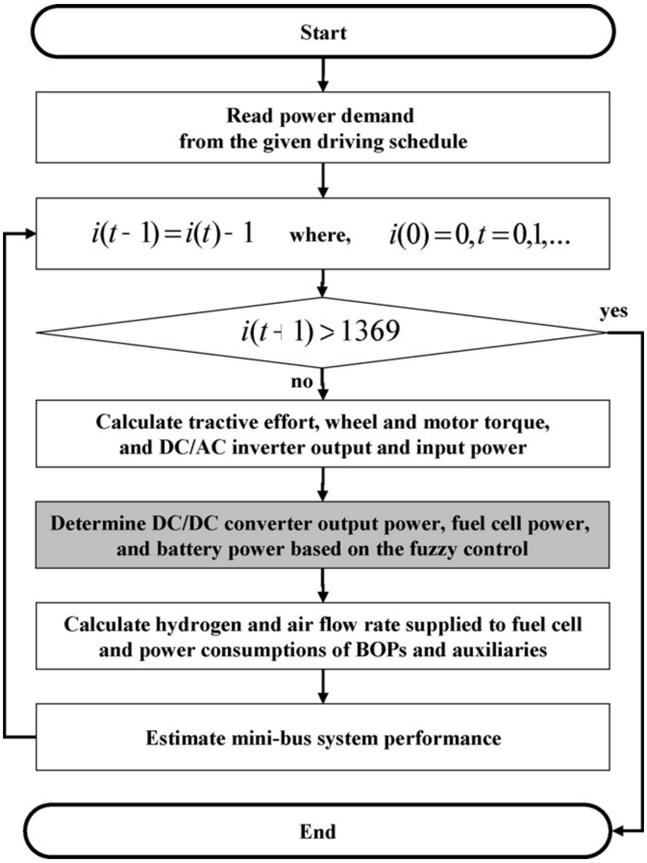

Fig. 2. Algorithm of the proposed simulator.

troller divides the power required from the motor of the mini-bus into the FCS and the battery. Finally, the mini-bus is driven using the power supplied from the DC/AC inverter.

2.2. Simulator algorithm

The proposed simulator is based on the closed loop iterative backward facing method as shown in Fig. 2. Firstly, the power of the mini-bus required to drive is decided based on the given driving schedule and then the input power of the DC/AC inverter is calculated according to the required power. Secondly, the controller divides the input power of the DC/AC inverter into the fuel cell stack and the battery. Thirdly, the power consumption of the balance of plants (BOPs) to supply the fuel and air for the required stack power is estimated. The overall mini-bus efficiency including the fuel cell stack, the BOPs, the battery, and the vehicle itself is estimated by iteratively calculating the mentioned procedure during the whole driving schedule.

2.3. Fuzzy control based power distribution

The fuel cell and battery powers are determined based on the fuzzy logic controller according to the power demand and the

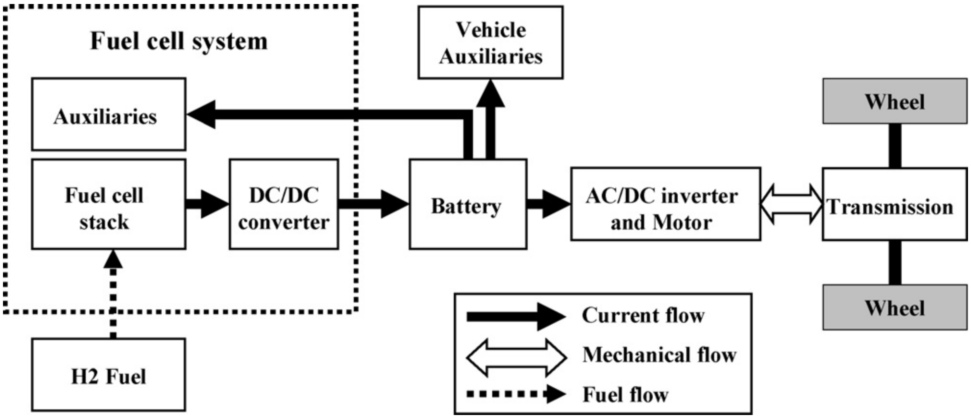

Fig. 1. Configuration of the fuel cell hybrid mini-bus.

Table 1
Rule base of fuzzy logic controller

Power demand	Battery SOC		
	Low	Medium	High
Low	High	Medium	Low
Medium	High	High	Medium
High	High	High	High

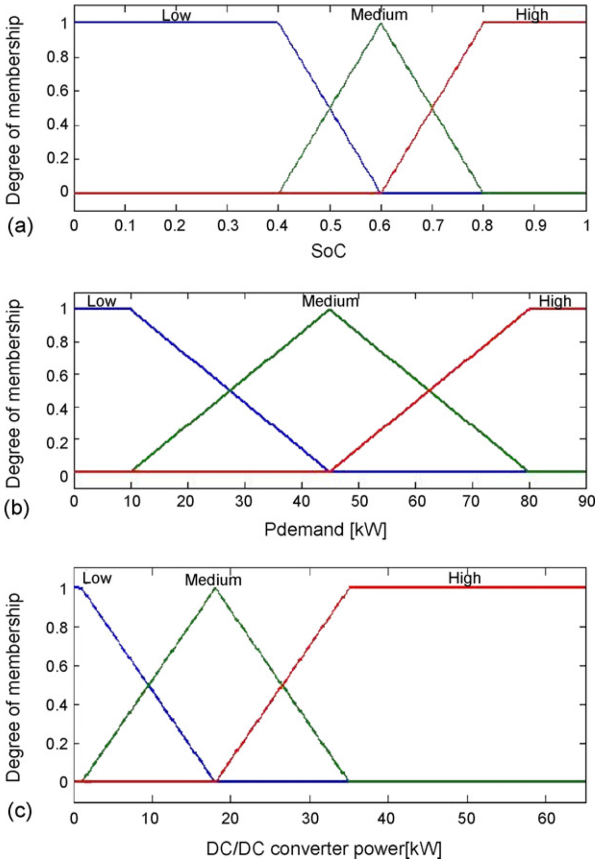

Fig. 3. Membership function of fuzzy logic controller: (a) input (SOC); (b) input (power demand); (c) output (DC/DC converter power).

battery SOC. The power demand means the power of the mini-bus required to drive. When the required power of the mini-bus is high, we can easily decide that both the fuel cell and the battery have to supply the power to the vehicle, however, when the required power is low, the decision of the power distribution between the fuel cell and the battery is changeable according to the current SOC of the battery. We just empirically guess as the followings. In case of the low SOC, the fuel cell power is needed to increase to fast charge the battery irrespective of the power demand. On the other hand at the high SOC, the fuel cell power has to decrease to slowly charge the battery or not to charge. However, the control of the power distribution is still ambiguous according to the current state of the power demand and the battery SOC. It is validated by Jeong at al. [1] that the fuzzy controller is very effective to optimally distribute the relative power between the fuel cell and the battery based on the experimental knowledge and its efficiency is better than the existing controllers. Table 1 shows the rule base of the fuzzy logic controller. For example, if the power demand is low and the battery SOC is low then the fuel cell power is high. Fig. 3 shows the input and output membership functions used in this work. The details about the fuzzy logic controller are referred to [1].

2.4. Modeling

The proposed simulator has many kinds of performance models such as the stack, the battery, the controller, the inverter/converter, the air blower, the water pump, and the fan. At the first, the fuel cell applied to the hybrid mini-bus is a polymer electrolyte membrane fuel cell (PEMFC) and we have made the fuel cell stack for a mini-bus. Its performance models are built based on the test data of the fuel cell stack we made. Fig. 4 (a) shows the performance curve of the fuel cell stack. The actual values are the results of the experiment and the estimated values are calculated by the performance model. Generally, the stack performance decrease by increasing the stack current like the curve in the Fig. 4 (a) because of the voltage drop of the stack. The detail causes of voltage drop of the fuel cell stack are explained in [7]. Fig. 4 (b) is the performance curve of the FCS including the stack and the BOPs. In case of the FCS we made, the worst performance is shown when it is operated at less than 5 kW and then the performance is gradually decreased by increasing the operating power of FCS.

At the second, the battery for the mini-bus consists of n 85Ah sub-battery. The power charged into the battery at each dt is calculated by equations from (1) to (9) where, the relationship between the battery internal resistance and the battery depth of discharge (DOD) is fitted with the test data. On the other hand, the power discharged from the battery at each dt is calculated by Eqs. (10) and (11) instead of Eqs. (4) and (8). The details about equations from (1) to (11) are referred to [8].

$$E(k-1) = 6((1-\mathrm{DOD}(k-1))0.22 + 1.945)n \quad (1)$$

$$R = f(\mathrm{DOD})n \quad (2)$$

$$I_{\mathrm{bat}}(k-1) = (E(k-1) - \sqrt{E(k-1)^2 - 4RP_{\mathrm{bat}}(k)})/2R \quad (3)$$

$$\mathrm{CR}(k) = \mathrm{CR}(k-1) + (\mathrm{d}t I_{\mathrm{bat}}(k-1)^{(1+C1)})/3600 \quad (4)$$

$$\mathrm{DOD}(k) = \mathrm{CR}(k)/C_{\mathrm{p}} \quad (5)$$

$$\mathrm{SOC}(k) = 1 - \mathrm{DOD}(k) \quad (6)$$

$$E(k) = 6((1-\mathrm{DOD}(k))0.22 + 1.945)n \quad (7)$$

$$I_{\mathrm{bat}}(k) = (E(k) - (E(k)^2 - 4RP_{\mathrm{bat}}(k))^{0.5})/2R \quad (8)$$

$$V_{\mathrm{bat}}(k) = E(k) - RI_{\mathrm{bat}}(k) \quad (9)$$

$$\mathrm{CR}(k) = \mathrm{CR}(k-1) + (\mathrm{d}t(I_{\mathrm{bat}}(k-1))^{1+C2})/3600 \quad (10)$$

$$I_{\mathrm{bat}}(k) = (-E(k) + (E(k)^2 + 4RP_{\mathrm{bat}}(k))^{0.5})/2R \quad (11)$$

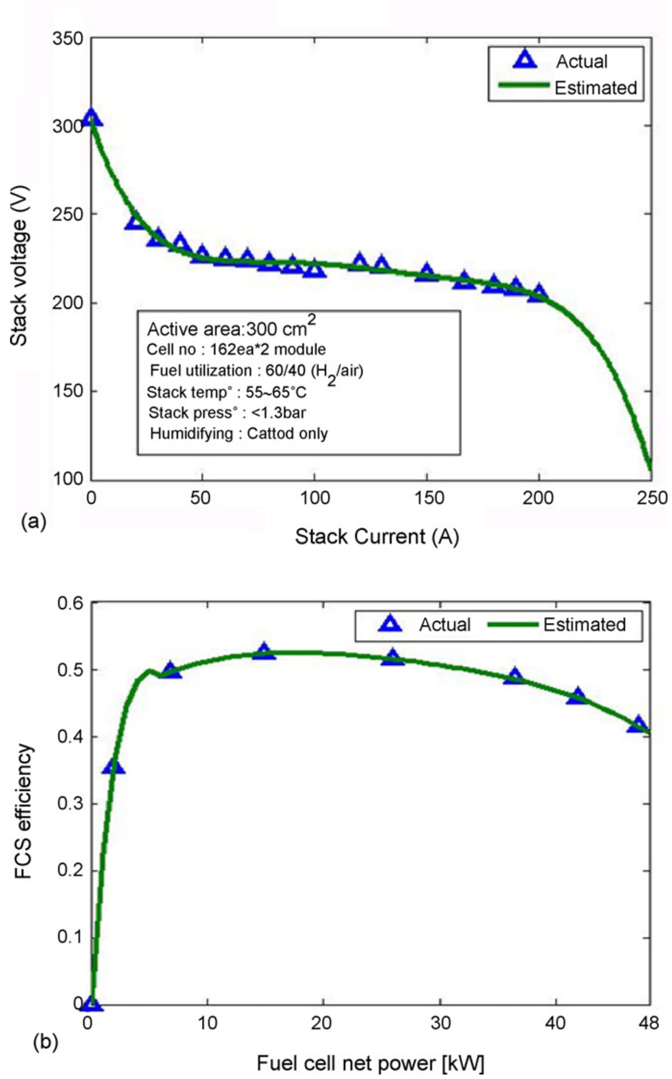

Fig. 4. Polarization curve of a fuel cell stack: (a) IV performance curve; (b) fuel cell power vs. efficiency curve.

2.5. Hybrid mini-bus performance indices

The performance index is the efficiency of the mini-bus system (Eq. (12)). $F_{H_2}LHV_{H_2}$ the energy of the hydrogen fuel supplied into the fuel cell stack and its details is referred to [7]. the P_{fchv} is the power supplied into the mini-bus to drive. P_{fchv} is calculated by subtracting the loss power of the DC/DC converter and DC/AC inverter, the parasitic power of the BOPs, and auxiliary power of the vehicle from the summation of the power generated at the stack and the battery power of charge or discharge (P_{bat}).

$$\eta_{fchv} = \frac{P_{fchv}}{(F_{H_2}LHV_{H_2}10^{-3} + P_{bat})} \tag{12}$$

3. Calculation

3.1. Driving schedule

The performance of the mini-bus needs to be validated based on the city's driving schedule since the mini-bus is supposed to be driven repetitively going a round on the city area. The driving schedule selected in this simulation is the urban dynamometer driving schedule (UDDS) contained in 40 code of federal regulations (CFR) Part 86 Appendix I supplied by Environmental Protection Agency (EPA). This is commonly called the "LA4" or "the city test" and represents city driving conditions. It is usually used for light duty vehicle testing.

3.2. Optimal engine sizing for the hybrid mini-bus

The capacities of the fuel cell stack and the battery is optimally designed based on the UDDS. The objective function is to maximize the efficiency of the mini-bus system (Eq. (12)) during one cycle of the given driving schedule. The decision variables are the capacity of the fuel cell stack and the number of sub-batteries. The efficiency is estimated based on the simulator by changing the capacity of the fuel cell stack and the number of the sub-batteries. The stack capacity is change from 30 kW to 70 kW and the number of the sub-batteries is change from 16 to 30. The simulation results show in Table 2. The maximum efficiency of the mini-bus is shown as 38% at the fuel cell power of 40 kW and the sub-battery number of 18. Those are represented with bold values in the table. Furthermore, it is shown that the vehicle performance is lower by becoming estranged from the optimal engine size determined by the proposed method. It is noted that the excessive or less capacity of the fuel cell and the battery occurs the degradation of the mini-bus performance. Finally, the optimal power ratio between the fuel cell stack and the battery can estimate as 4:3 since the series battery with 18 sub-batteries generates the average power of 30 kW.

4. Results and discussion

Figs. 5–7 show the performance of the hybrid mini-bus designed by the proposed method during UDDS. As shown Fig. 5, the fuel cell hybrid mini-bus shows the good power distribution between the fuel cell and the battery to meet the power required to drive. Namely, the battery SOC is stably maintained between 0.4 and 0.7 through the given driving schedule (Fig. 6) as well as the operating power of the fuel cell stack is mainly maintained between 7 kW and 30 kW. The mentioned operating

Table 2
Results of the optimal engine sizing for the hybrid mini-bus

Sub-batteries number	Stack capacity (kW)				
	30	**40**	50	60	70
16	11	34	35	34	32
18	28	**38**	36	35	34
20	32	31	29	33	35
22	32	33	30	31	30
24	22	31	32	32	32
26	16	33	33	33	32
28	22	33	34	34	33
30	24	33	35	34	33

The efficiency of the mini-bus system (%) according to the change of the stack capacity and the sub-batteries number.

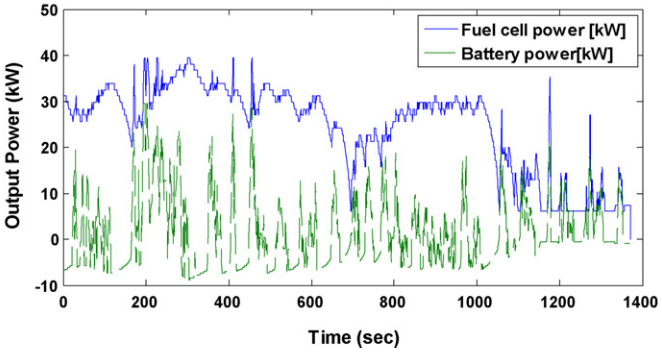

Fig. 5. Power management for the hybrid mini-bus with optimal design value during UDDS.

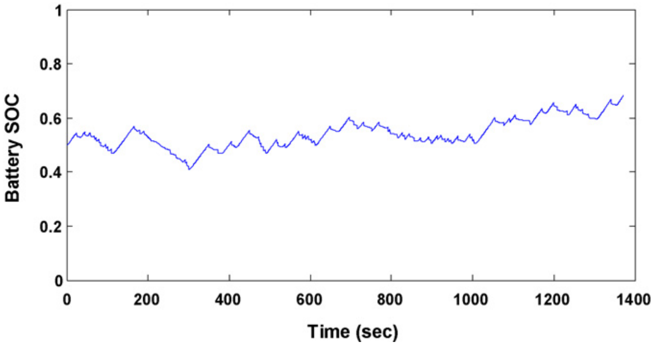

Fig. 6. Battery SOC for the hybrid mini-bus with optimal design value during UDDS.

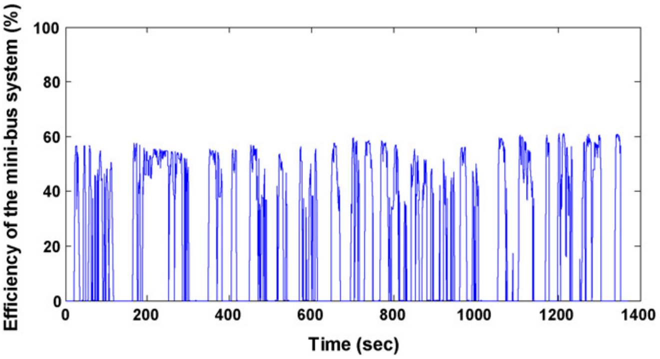

Fig. 7. System efficiency for the hybrid mini-bus with optimal design value during UDDS.

range of the fuel cell power (from 7 kW to 30 kW) has the high efficiency of the FCS. Therefore the system efficiency of the fuel cell hybrid mini-bus is moved near average efficiency 38% during the driving as shown Fig. 7.

5. Conclusion

The simulation based fuel cell design and performance test in design phase are very necessary to improve the real system's performance as well as to reduce the significant amount of cost and time arising from the trials for the system development. In this paper, the optimal engine sizing between the fuel cell and the battery has been performed for the fuel cell/battery hybrid mini-bus. The proposed design method is based on the simulator considering with the component models to calculate the efficiency of the fuel cell, battery, BOPs, and so on. As a result, the optimally designed capacities of the fuel cell and battery are determined as 40 kW and 30 kW, respectively. Using the proposed simulator, the followings are verified by applying the optimal design values into the target mini-bus. Firstly, the system efficiency has been maintained near the good efficiency during the driving. Secondly, the power distribution has been stably operated although the power demand and the battery SOC are very changeable through the driving schedule. The proposed method to design and to pre-test the performance expects to be applied effectively design the many kinds of the fuel cell hybrid vehicles.

Acknowledgements

This work was supported partly by Ministry of Science and Technology and by Ministry of Commerce, Industry and Energy.

References

[1] K.-S. Jeong, W.-Y. Lee, Trans. Korean Hydrogen New Energ. Soc. 129 (1) (2004) 1–11.
[2] P. Rodatz, G. Paganelli, A. Sciarretta, L. Guzzella, Contol Eng. Pract. 13 (2005) 41–53.
[3] D. Asssanis, G. Delagrammatikas, R. Fellini, Z. Filipi, J. Liedtke, N. Michelena, P. Papalambros, D. Reyes, D. Rosenbaum, A. Sales, M. Sasena, Mech. Struct. Mach. 27 (4) (1999) 393–421.
[4] A. Sciarretta, L. Guzzella, C.H. Onder, Automatisierungstechnik 51 (2003) 195–203.
[5] P. Atwood, S. Gurski, D. Nelson, K. Wipke, T. Markel, Degree of hybridization modeling of a hydrogen fuel cell PNGV-class vehicle, SAE Paper No. 2002-01-1945.
[6] M.-J. Kim, H. Peng, J. Power Sources 165 (2) (2006) 819–832.
[7] J. Larminie, A. Dicks, Fuel Cell Systems Explained, second ed., Wiley, 2003.
[8] J. Larminie, J. Lowry, Electric Vehicle Technology Explained, Wiley, 2003.