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Review

Energy management strategies of a fuel cell/battery hybrid system using fuzzy logics

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Abstract

Hybrid power systems with fuel cells and batteries have the great potential to improve the operation efficiency and dynamic response. A proper load management strategy is important for both better system efficiency and endurance of hybrid systems. In this paper, a fuzzy logic algorithm has been used to determine the fuel cell output power depending on the external power requirement and the battery state of charge (SoC). If the power requirement of the hybrid system is low and the SoC is low, then the greater part of the fuel cell power is used to charge the battery pack. If the power requirement is relatively high and the SoC is also high, then the fuel cell and the battery are concurrently used to supply the required power. These if–then operation rules are implemented by fuzzy logic for the energy management of the hybrid system.

The strategy is evaluated using simulation and experimental results. The results show that the operation efficiency of hybrid system was improved and the battery SoC maintained at reasonable level. The control scheme can be used to optimize the operational efficiency of hybrid power generation system.

Keywords: Fuel cell; Battery; Hybrid; Fuzzy

Contents

1. Introduction

Fuel cells are considered as an alternative for electric power generation in transportation and stationary applications. The hybrid system has many advantages. The battery can be used to meet the peak power demand; hence, the size of the fuel cell stack can be minimum. The hybrid can be operated more efficiently than single fuel cell system. Initial manufacturing cost of the fuel cell will be lesser [1–3]. Fuel cells are inefficient to respond to the fast load and high peak power demanded. Fuel cell/battery hybrid systems can combine the

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high energy density of fuel cells and the high power density of batteries. When battery current is high, the internal resistance of the battery increases which leads to the decrease in battery efficiency. Over-charge and over-discharge can cause the battery damage. Charge–discharge of the battery must be controlled according to battery SoC and battery SoC must remain at reasonable level. Therefore, proper load management strategy is important for better system efficiency in the hybrid system.

The objective of this work is to develop an efficient hybrid operating system. The system should be able to deliver the power requirement, maintain the battery SoC and also ensure the safe and durable operation. The methodology followed is the simulation as well as the experiment. The components were tested to obtain the data to be used as input for the simulation and experiments. Simulation of the integrated fuel cell/battery hybrid system was carried out to identify the optimum operating conditions. Experiments were also carried out with the hybrid system. The results were compared to validate the simulation.

2. Component test and modeling of fuel cell battery hybrid system

2.1. Fuel cell system and electric devices

Fig. 1 shows the configuration of fuel cell/battery hybrid system including fuzzy logic controller. The hybrid system consists of a fuel cell, a battery pack, a DC/DC converter, a DC/AC inverter, a Battery Management System (BMS) and a controller. Fuel cell system used in this study stacks 42PEM fuel cells together in series. Fig. 2 shows the characteristics of fuel cell system. The maximum power of fuel cell is 1.4 kW. Table 1 summarizes the specifications of fuel cell and electric devices.

To apply fuel cell to general power systems it is necessary to boost the voltage of fuel cell or to increase the number of cells. The roles of the DC/DC booster converter are increasing

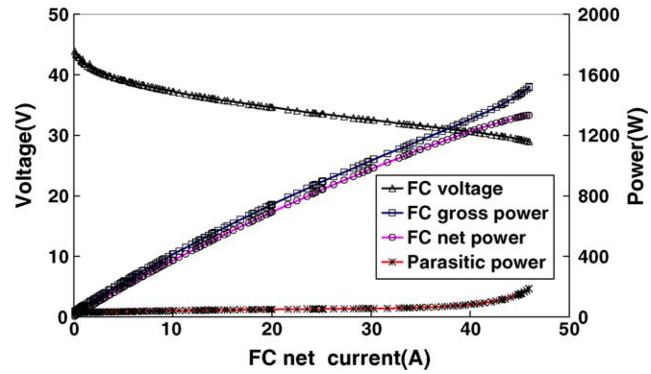

Fig. 2. Fuel cell system characteristics.

voltage of fuel cell, control of fuel cell power and regulating voltage. Operation of the fuel cell system is controlled by the fuel cell controller which in turn is coupled to the fuzzy logic controller. The state of each component is checked and controlled to get the optimum performance. Fig. 3 shows the fuel cell system net efficiency ($\eta_{\text{fc,net}}$) and DC/DC converter output efficiency (η_{dc}) as a function of DC/DC converter output power which are expressed as Eqs. (1) and (2). Fig. 4 shows DC/AC inverter efficiency (η_{inv}) which is expressed as Eq. (3). Table 2 presents the constants used in Eqs. (1)–(3).

$$P_{\text{fuel}} = \dot{m}_{\text{H}_2}\,\text{HHV} = a + bP_{\text{dc}} + cP_{\text{dc}}^2 + dP_{\text{dc}}^3 + eP_{\text{dc}}^4 + fP_{\text{dc}}^5, \quad \eta_{\text{dc,out}} = \frac{P_{\text{dc}}}{P_{\text{fuel}}} \tag{1}$$

$$P_{\text{fc,net}} = a + bP_{\text{dc}} + cP_{\text{dc}}^2 + dP_{\text{dc}}^3 + eP_{\text{dc}}^4 + fP_{\text{dc}}^5, \quad \eta_{\text{fc,net}} = \frac{P_{\text{fc,net}}}{P_{\text{fuel}}} \tag{2}$$

$$P_{\text{inv,i}} = a + bP_{\text{inv,o}} + cP_{\text{inv,o}}^2 + dP_{\text{inv,o}}^3, \quad \eta_{\text{inv}} = \frac{P_{\text{inv,o}}}{P_{\text{inv,i}}} \tag{3}$$

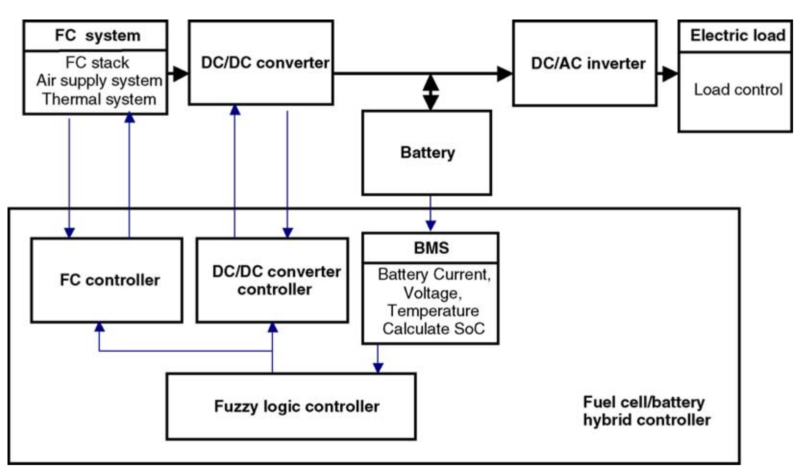

Fig. 1. Configuration of the fuel cell battery hybrid system.

Table 1
Specifications of the hybrid system

Fuel cell system				
No. of cell	Operating range (V)	Rated voltage (V)	Rated current (A)	Rated power (Kw)
42	20–42	25	56	1.4
Battery				
Type	Capacity (Ah/h)	No. of module		Nominal voltage (V)
Lead acid	100/10	4		48
DC/DC converter				
Input voltage	Output voltage (V)	Input current (A)		Maximum output current
22–58	40–60	0–100		96
DC/AC inverter				
Continuous power (W)	Input voltage (V)	Output voltage (V/Hz)	Maximum input current (A)	Maximum output current (A)
3000	42–68	220/60	197	41

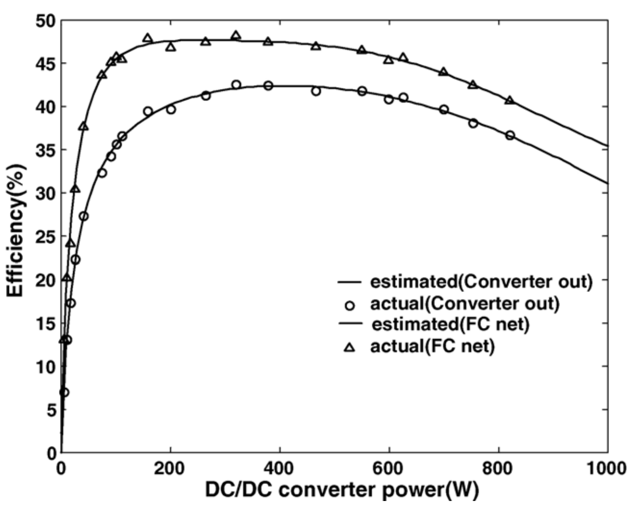

Fig. 3. Fuel cell system net and DC/DC converter efficiency.

where P_{fuel} is the unit time hydrogen energy input; P_{dc} is the DC/DC converter output power; $P_{fc,net}$ is the fuel cell net output power; $P_{inv,i}$ is the DC/AC inverter input power; $P_{inv,t}$ is the DC/AC inverter output power. The LHV is lower heating value of hydrogen.

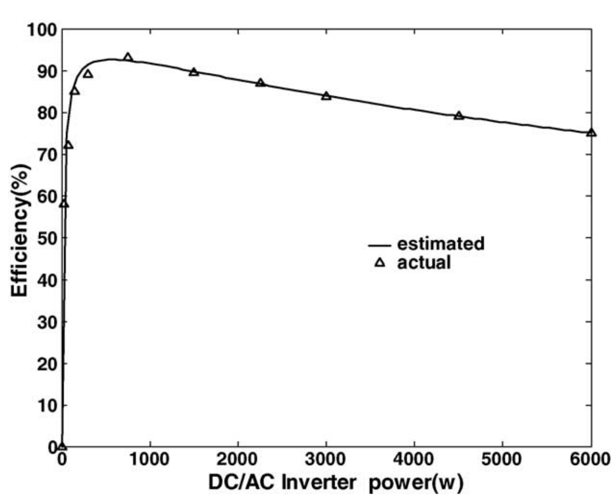

Fig. 4. DC/AC inverter efficiency.

2.2. Battery

The objectives of battery testing are to obtain basic parameters to be used in the model and also to use the control strategies. The following tests were carried out on the battery.

- Capacity test: relationship between charge–discharge rate and capacity.
- Charge–discharge test: internal resistance, voltage versus SoC.
- Cycle test: battery voltage–current behavior.

Some other data were obtained from the battery manufacturer.

The available capacity of the battery can be different from the rated value when battery is discharged under different conditions. The available capacity can decrease rapidly at lower temperature and high discharge current. Eq. (4) represents the available capacity, which is determined by temperature and discharge current. The results are described in Fig. 5.

$$C_i = 119.8I^{-0.0872} + 74.646\exp^{-0.12235\times I} + (-0.0011T + 1.2337T - 24.005) \quad (4)$$

Eq. (5) represents variation of battery SoC at discharge state, and Eq. (6) represents variation of battery SoC at charge state.

$$\Delta \mathrm{SoC} = -\frac{\Delta C_i}{C_i} = -\frac{I_i \Delta t}{3600 C_i} \quad (5)$$

Table 2
Constant for Eqs. (1)–(3)

	Fuel (1)	FC net (2)	DC/AC inverter (3)
a	61.641	1.3322	19.498
b	2.2546	1.426	1.0103
c	−0.0006246	−0.002023	6.34E−05
d	1.60E−06	4.87E−06	−1.68E−09
e	−1.32E−09	−5.19E−09	
f	1.26E−12	2.06E−12	

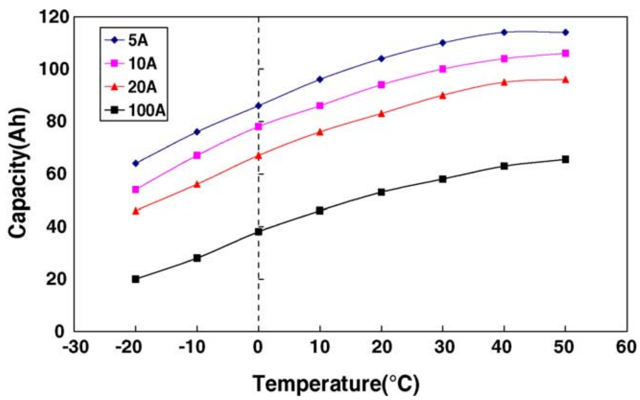

Fig. 5. Capacity vs. discharge rate, temperature.

$$\Delta \mathrm{SoC} = -\frac{\Delta C_{\mathrm{i}}}{C_{\mathrm{ref}}} = \frac{\alpha I_{\mathrm{i}} \cdot \Delta t}{3600 C_{\mathrm{ref}}} \tag{6}$$

where C_{ref} is reference battery capacity; α is the charge capacity constant, which means the efficiency of battery charge at different temperature and charging rate (current), which is summarised in Table 3. The variation of battery SoC is the effective charge ratio to reference battery capacity.

If the current for unit time is known, the battery SoC can be determined as by Eq. (7).

$$\mathrm{SoC} = \mathrm{SoC}_{\mathrm{initial}} + \int_0^t \Delta \mathrm{SoC}\, \mathrm{d}t \tag{7}$$

Four modules of 100 Ah lead acid battery were connected in series. Battery SoC was calculated from battery capacity equation and battery current. Battery capacity and resistance were considered to calculate the efficiency of system and battery. Fig. 6 shows the efficiency map of battery in the SoC-power plane. The battery operates most efficiently at lower power levels and low SoC when battery is charged. On the other hand when battery is discharged battery it operates efficiently at lower power level and high SoC.

Table 3
Battery charge capacity constant (α)

SoC (%)	Current (C)	Battery temperature			
		10°C	20°C	30°C	40°C
0–70	0.1	0.9	1	0.98	0.95
	1	0.73	0.8	0.77	0.73
71–90	0.1	0.87	0.95	0.93	0.91
	1	0.71	0.75	0.72	0.71
91–96	0.1	0.85	0.93	0.9	0.89
	1	0.68	0.71	0.7	0.69
96–100	0.1	0.8	0.91	0.88	0.87
	1	0.65	0.68	0.66	0.64

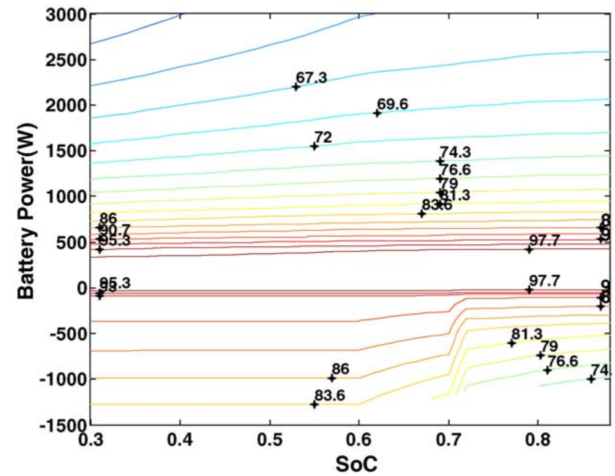

Fig. 6. Efficiency map of battery.

3. Fuel cell/battery hybrid system efficiency

Efficiency of power system is defined as the ratio of the useful energy output to total energy input. The efficiency of hybrid system can be classified as following three cases depending on how battery works in the system. At battery charge mode, energy input is fuel energy and useful energy output is AC energy output minus battery charge energy. At battery discharge mode, energy input is fuel energy plus battery discharge energy and useful energy output is AC energy output.

(i) Battery discharging mode

$$\eta_{\mathrm{sys},1} = \frac{W_{\mathrm{ac}}}{\dot{m}_{\mathrm{H}_2}\,\mathrm{HHV} + W_{\mathrm{E}}}, \quad W_{\mathrm{E}} = \frac{V_{\mathrm{bat,d}}\, I_{\mathrm{bat,d}}}{\eta_{\mathrm{c,mean}}\, \eta_{\mathrm{discharge}}},$$
$$\eta_{\mathrm{c,mean}} = \frac{\sum_c (\eta_{\mathrm{charge}}\, V_{\mathrm{bat,c}}\, I_{\mathrm{bat,c}}\, t)}{\sum_c (V_{\mathrm{bat,c}}\, I_{\mathrm{bat}}\, t)/\eta_{\mathrm{dc,out}}} \tag{8}$$

(ii) Battery charging mode

$$\eta_{\mathrm{sys},2} = \frac{W_{\mathrm{ac}} - W_{\mathrm{L}}}{\dot{m}_{\mathrm{H}_2}\,\mathrm{HHV}}, \quad W_{\mathrm{L}} = V_{\mathrm{bat,c}}\, I_{\mathrm{bat,c}}\, \eta_{\mathrm{charge}} \tag{9}$$

(iii) Only fuel cell operation mode

$$\eta_{\mathrm{sys},3} = \frac{W_{\mathrm{ac}}}{\dot{m}_{\mathrm{H}_2}\,\mathrm{HHV}} \tag{10}$$

where W_{ac} indicates AC electric power. $V_{\mathrm{bat,d}}$ and $I_{\mathrm{bat,d}}$ indicate the voltage and the current from the battery, respectively when the battery discharged. $\eta_{\mathrm{discharge}}$ is the discharging efficiency of battery. W_{E} indicates the battery discharged power and W_{L} is the actual charged power to battery due to charging efficiency. $V_{\mathrm{bat,c}}$ and $I_{\mathrm{bat,c}}$ are the voltage and the current when battery is charged. η_{charge} indicates the battery charging efficiency.

Because the battery discharge efficiency is higher than fuel cell system efficiency hybrid system efficiency can be calculated higher than fuel cell system maximum efficiency. In the

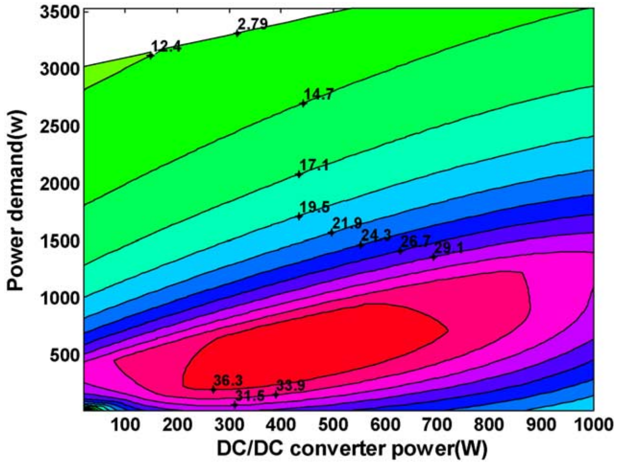

Fig. 7. Hybrid system efficiency (SoC = 0.8).

hybrid system, battery must be charged by output energy of fuel cell system. So, we considered the mean battery charge efficiency ($\eta_{c,mean}$). Mean battery charge efficiency is defined as the ratio of total charged energy to total fuel energy input for charging battery. Figs. 7 and 8 show the efficiency contour of hybrid system in the DC/DC converter power and power demand plane. When power demand is lower than 1000 W and DC/DC converter power range 200–700 W, hybrid system efficiency is relatively high. Fig. 9 shows the DC/DC converter power at maximum efficiency in SoC-AC power demand plane. Fig. 10 shows the maximum hybrid system efficiency. Theses figures show the criterion to maximize the instantaneous efficiency.

Hybrid system efficiency varied according to the path of battery charge–discharge. Instantaneous efficiency and cycle efficiency can be considered in the hybrid system. If hybrid system operates to increase the instantaneous efficiency in some cases it can be impossible to maintain the battery SoC. On the other hand, when hybrid system operates to maintain the battery SoC system, efficiency can be reduced. So, it is necessary to operate the fuel cell system within high efficiency area and to maintain battery SoC at reasonable level. For these purposes, fuzzy logic controller was used.

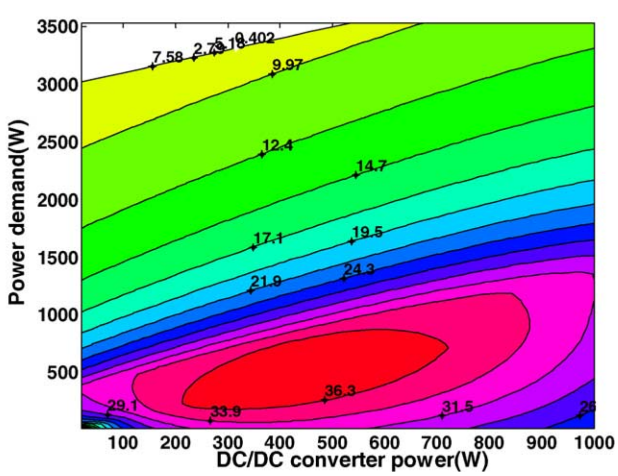

Fig. 8. Hybrid system efficiency (SoC = 0.4).

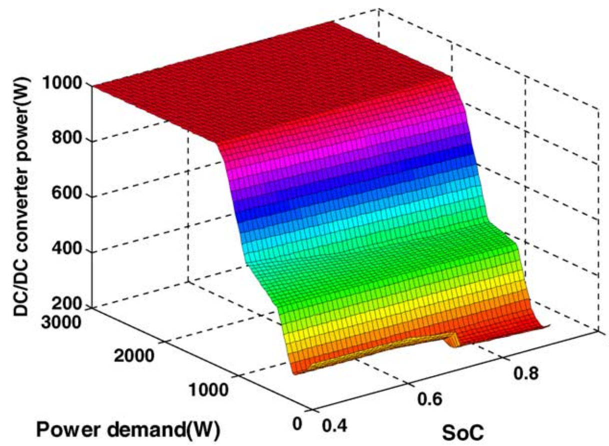

Fig. 9. DC/DC converter power at maximum efficiency.

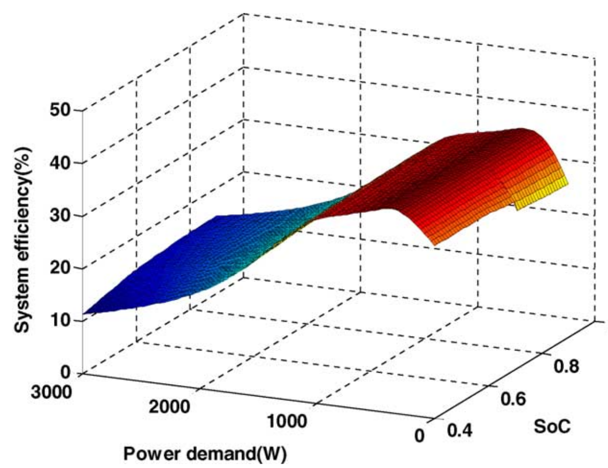

Fig. 10. Maximum hybrid system efficiency.

4. Energy management strategies

The energy in the system should be managed in such way that the power supply is satisfied consistently, the battery is sufficiently charged at all times and the overall system efficiency is optimal. The power controller is used to determine how much power is needed for DC/AC inverter and how much to charge the battery. To determine the optimal power split and to increase the efficiency, fuzzy logic control is used. Fuzzy logic controller relates the controller output to the inputs using a list of if–then statements called rules. The if part of the rules refers to adjectives that describe regions of input variables. A particular input value belongs to these regions to a certain degree, represented by the degree of membership function. The then part of rules refers to value of the output variable. To obtain the output of the controller, the degree of membership of the if parts of all rules are averaged and weighted by the degrees of membership [3,4].

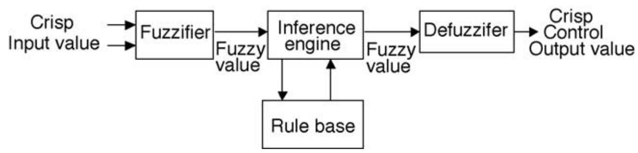

Fig. 11. Structure of fuzzy logic controller.

Table 4
Rule base of fuzzy logic controller

If SoC is low then DC/DC converter is high
If SoC is medium and power demand is low then DC/DC converter power is medium
If SoC is high and power demand is low then DC/DC converter power is low
If SoC is high and power demand is medium then DC/DC converter power is medium
If power demand is high then DC/DC converter power is high

Fig. 11 shows fuzzy logic control analysis method. The inputs of the fuzzy logic controller are DC/AC inverter input power and battery state of charge (SoC). The output of fuzzy logic controller is DC/DC converter output power. Fuel cells are directly connected to DC/DC converter so that the power of fuel cell is determined by DC/DC converter output power control. If the power requirement of the hybrid system is low and the SoC is low then the greater part of the fuel cell power is used to charge the battery pack. If the power requirement is relatively high and the SoC is high then the fuel cell and the battery are concurrently used to supply the required power (Table 4).

The membership function of inputs, output and rules were determined by simulation to increase the system efficiency and to maintain the battery SoC. Experiment data of each component such as fuel cell, battery, DC/DC converter and DC/AC inverter were used in simulation. The membership function of inputs and output are represented in Fig. 12. Table 2 presents the rules of fuzzy logic controller. Fig. 13 shows the result of fuzzy controller.

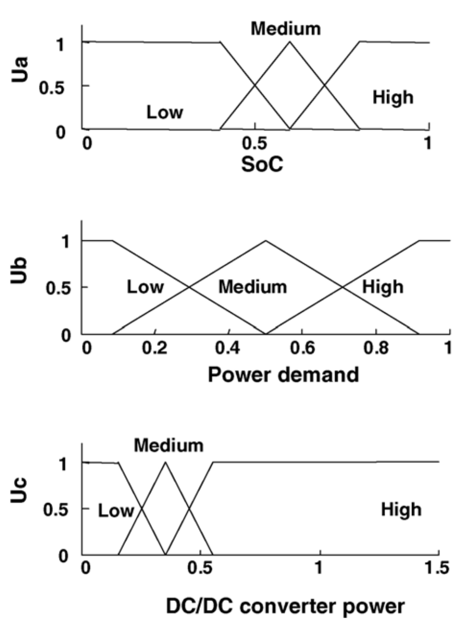

Fig. 12. Input and output membership function of fuzzy logic controller.

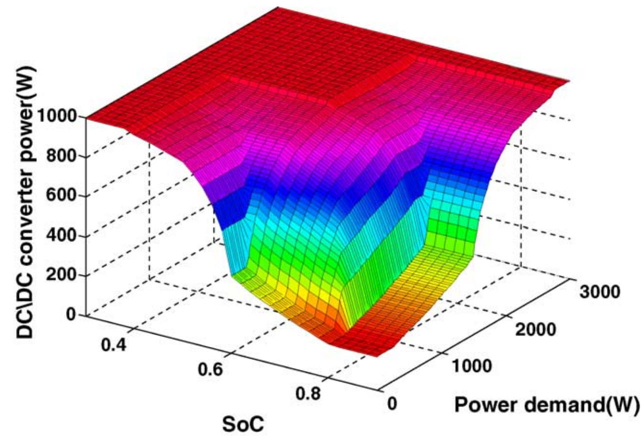

Fig. 13. Output result of fuzzy logic controller.

5. Cycle test result and simulation

Profile of electricity use has a significant effect on determining the energy management strategy. In this study it is considered that fuel cell/battery hybrid system supplies the electricity for residential applications. NTIS report gives a mean daily profile for the electricity consumption by light and appliances for residence. In this report average electric loads for each hour are about 0.2–1.6 kWh. It is observed that the peak electricity demand exceeds 6.4 kW [5]. Because data for electricity use for each second were not sufficient we used the electricity load profile as in Fig. 14.

Fig. 15 shows the simulation result of battery SoC history in 40 cycles of AC electricity demand. The result shows that battery SoC can be maintained at a reasonable level.

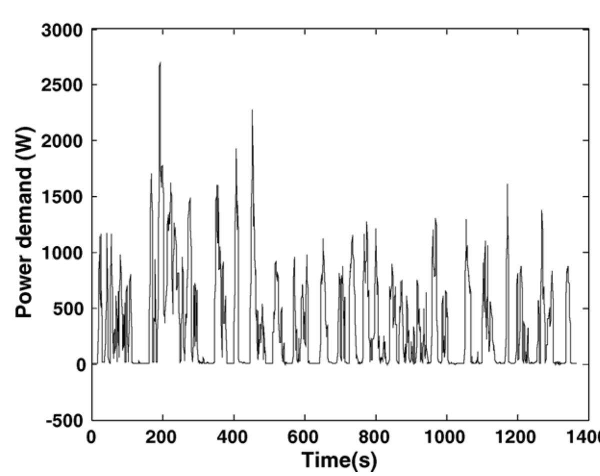

Fig. 14. AC electricity demand.

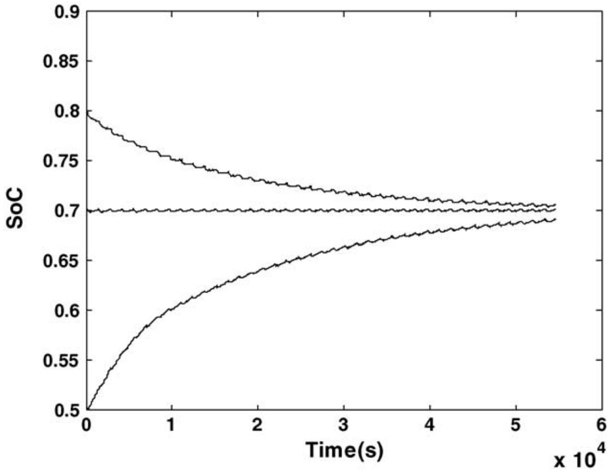

Fig. 15. Simulation result of battery SoC history in 40 cycles.

Hybrid system performance highly depends on the energy capacity stored in the battery. The charge–discharge current has a significant effect on this battery capacity. Many battery capacity estimation approaches for the lead acid battery has been investigated such as the impedance measurement approach and the artificial neural network modeling approach [6,7].

System identification deals with the problem of building mathematical models of dynamical system based on observed data from the system [8]. In this study AutoRegressive with eXternal input (ARX) method is used to estimate battery voltage. Battery current directly can be calculated from the result of dividing battery power by battery voltage. Figs. 16 and 17 show battery voltage and current during the cycle. Fig. 18 shows the battery SoC. As seen in Figs. 16–18, the simulation values are in good agreement with the experimental data. The result data of fuel cell system and DC/DC converter power showed more accuracy than battery data.

Airflow response is most slow in the hybrid system. Fuel cell system response is at the mercy of airflow. To avoid the deficiency of air in the fuel stack outputs of fuzzy logic controller outputs are moving averaged. DC/DC converter power was controlled by this moving averaged result. Fig. 19 shows experimental result of inverter, FC and battery power. Battery response for load changes is faster than fuel cell system. Battery supplied power to meet the fast load change and fuel cell power changed slowly for fuel cell stack safety and durability. Fig. 20 shows the experiment result of energy usage and primary energy loss when battery initial SoC is 0.68. FC loss was 47.85% and AC output energy can be used to operate electric device was 31.65%.

If the performance of fuel cell system has same ratio as in Fig. 2, simulation results of pure fuel cell system efficiency are summarized in Table 5. When maximum fuel cell system

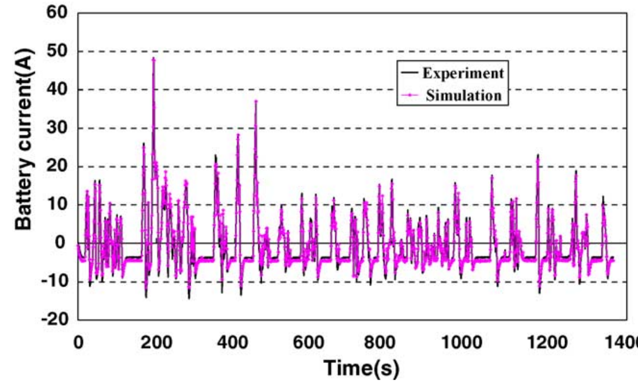

Fig. 17. Battery voltage.

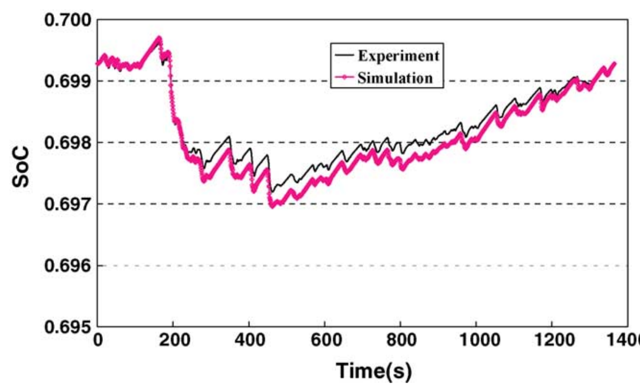

Fig. 18. Battery SoC.

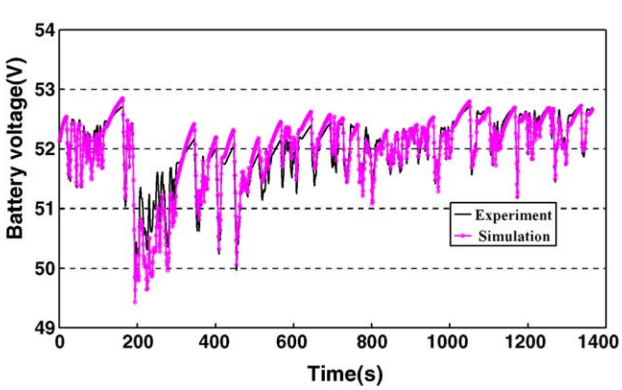

Fig. 16. Battery current.

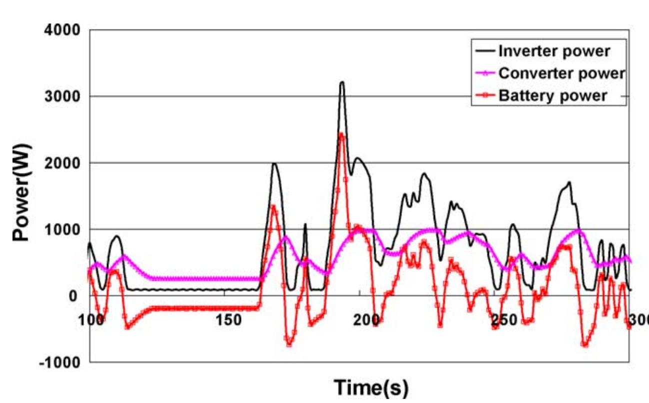

Fig. 19. Experimental result of inverter, FC, battery power.

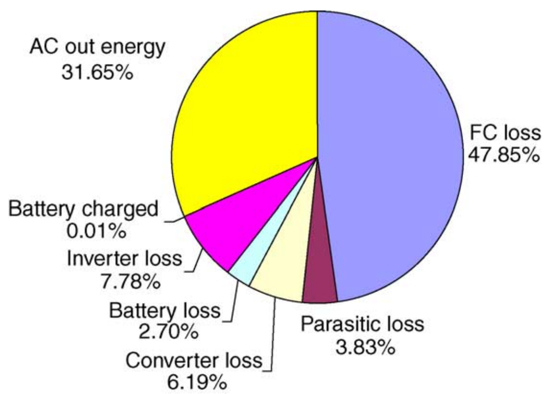

Fig. 20. Energy usage and primary loss (initial SoC = 0.68).

Table 5
Pure fuel cell cycle efficiency

Cycle efficiency (%)	Maximum FC net power (kW)
30.85	4
29.35	5
27.88	6
26.52	7
25.25	8
24.1	9

power is 4 kW, the cycle efficiency was 30.85%. The cycle efficiency decreased as fuel cell size increased. When fuel cell supplies the whole power of residential application, more than 6.4 kW of fuel cell maximum power is necessary to meet the power demand. When maximum FC net power was 6 kW, the calculated cycle efficiency was 27.88%. This efficiency is 4% lower than that of hybrid system.

6. Conclusion

This paper presents a study on control strategies for active power sharing in a hybrid fuel cell/battery power source to improve the system efficiency and battery life with acceptable load following capability.

All the system components (fuel cell system, battery, DC/DC converter, DC/AC inverter) were tested to obtain parameters to be used as inputs. Model equations are derived based on component test results. Simulation was performed to develop and verify control algorithms. Experiments were carried out to validate the simulation results. The efficiency maps of the components have been used to design the controller. Fuzzy logic has been developed and implemented to manage the hybrid power system. The results show that fuzzy logic can be used to optimize the operational efficiency of the fuel cell system and to keep the battery SoC at reasonable level.

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