International Journal of Automotive Technology, Vol. 6, No. 4, pp. 429–436 (2005)

1229–9138/2005/022–15

OPERATION ALGORITHMS FOR A FUEL CELL HYBRID ELECTRIC VEHICLE

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(Received 24 April 2004; Revised 28 February 2005)

ABSTRACT–In this paper, operation algorithms are evaluated for a fuel cell hybrid electric vehicle (FCHEV). Power assist, load leveling and equivalent fuel algorithm are proposed and implemented in the FCHEV performance simulator. It is found from the simulation results that the load leveling algorithm shows poor fuel economy due to the system charge and discharge efficiency. In the power assist and equivalent fuel algorithm, the fuel cell stack is operated in a relatively better efficiency region owing to the battery power assist, which provides the improved fuel economy.

KEY WORDS : Fuel cell, Proton exchange membrane, Fuel cell hybrid electric vehicle, Operation algorithm, Regenerative braking

NOMENCLATURE

i	: current [A]
m	: fuel consumption [kg/s]
E_b	: battery equivalent fuel consumption [kg/W·s]
E_{cell}	: fuel cell open circuit voltage [V]
F	: Faraday constant [Coulombs/mole]
N_{cell}	: number of cells in the stack
P	: power [kW]
R_i	: battery internal resistance [Ω]
SOC	: battery state of charge [%]
T	: torque [Nm]
U	: battery voltage [V]
V	: voltage [V]
W_i	: weight factor, $i = 1, 2, 3$
η	: efficiency

1. INTRODUCTION

Growing concerns on CO_2 reduction and limited energy sources have been demanding clean and better energy efficient vehicles without compromising any convenient features of the conventional internal combustion engine vehicles. To meet such demands, automotive manufacturers have investigated alternative drivetrains such as H_2/CNG driven engine, electric vehicles (EV), hybrid electric vehicles (HEV) and fuel cell electric vehicles (FCEV). In comparison of these alternate drivetrains, they show advantages and disadvantages at different criteria. Vehicle manufacturers claim that FCEVs are very promising in long term base in terms of performance, efficiency and compliance with emission reduction schedules (Yang, 2000).

Basically, a fuel cell vehicle uses a fuel cell stack instead of a battery as the major source of electric power to drive an electric traction motor. The simplest configuration is supplying hydrogen directly from a hydrogen tank stored in the form of compressed gas or cryogenic liquid.

Conventional fuel cell vehicles only use the fuel cell power for the vehicle propulsion. Hence the vehicle has no regenerative energy recovery in braking, and a long start-up time, and poor transient response with complex fuel cell and auxiliary system management. These shortcomings can be overcome by hybridization of FCEV using batteries. It is expected that a fuel cell hybrid electric vehicle (FCHEV) can offer faster transient response at start, the energy recuperation capability in the regenerative braking and more efficient system operation by adequate operation algorithm than FCEVs.

A FCHEV has two sources of on–board power. A power control strategy is needed to control the flow of power while taking reserves of energy in the storage device into account. There are two distinct extremes in the spectrum of control strategy. One is a system that uses a "thermostat" algorithm to command the fuel cell stack. In this mode, the battery must accommodate to all the transient power requirement. The other extreme commands the fuel cell stack to follow the actual wheel power whenever possible, which is similar to a conven-

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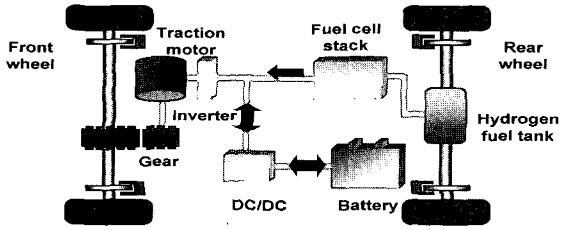

Figure 1. Structure of fuel cell hybrid electric vehicle.

tional automobile. Using this strategy, the fuel cell stack must operate over its entire range of power levels. For FCHEVs, fuel consumption depends on the way that the electrical energy stored in the batteries is substituted to the hydrogen energy. Therefore, FCHEV control strategy can be constructed according to the depth of discharge of the batteries from the viewpoint of the battery energy management. For most of the fuel cell stack and batteries under consideration, neither of these strategies would be the optimum strategy. The optimum strategy is highly dependent on the characteristics of the powertrain components and the planned use of the vehicle.

In this paper, operation algorithms which have been developed for the HEV's such as power assist algorithm (Matthew, 1995), load leveling algorithm (Hochgraf *et al.*, 1996) and equivalent fuel algorithm (Kim *et al.*, 1999, Zeolch *et al.*, 1998) are investigated for the FCHEV with some modifications by considering the fuel cell stack characteristics.

2. FCHEV OPERATION ALGORITHM

Figure 1 shows a structure of the FCHEV used in this study. The FCHEV used in this study consists of proton exchange membrane type fuel cells, an induction motor and a 6.5 Ah Ni-MH battery system. The traction motor is connected by a 10.03:1 reduction gear to the wheels of the vehicle. The DC/DC converter between the fuel cell stack and battery allows the fuel cell system to operate at a steady state independent of the battery voltage and of the electric load imposed by the drivetrain and auxiliaries. Compressed hydrogen is supplied directly to the fuel cell stack. The FCHEV used in this study adopts a front-wheel drive.

2.1. Power Assist Algorithm

In the power assist algorithm, the battery is used to assist the fuel cell in the start-up and acceleration mode while the fuel cell propels the vehicle as a primary power source. The general operation mode of the vehicle is divided into start-up, constant speed (cruise), acceleration, deceleration and fuel cell-off modes (Oh *et al.*, 2003), and control logic for each mode of operation is described in the following.

In the start-up mode, the vehicle starts only by the battery because the battery shows better response than the fuel cell stack. However, battery drive can be applied only when the battery state of charge (SOC) and the required power meet pre-determined condition. For instance, if the battery SOC becomes lower than the bottom limit, the battery is switched off and the fuel cell stack is used to start the vehicle.

In the constant speed mode, the vehicle runs at a constant speed or mild acceleration. If the battery SOC is high enough and demanded vehicle power is small, vehicle is propelled only by the battery since the fuel cell stack efficiency is poor in the low power region. If demanded vehicle power is medium, vehicle is propelled only by the fuel cell stack since the stack efficiency is relatively high in the medium power region. When the battery SOC is low, the FCHEV is driven only by the fuel cell stack and the battery is charged by fuel cell.

In the acceleration mode when the FCHEV requires high power, both battery and fuel cell stack are used to meet the high power requirement of vehicle.

The required vehicle power is calculated corresponding to the drive pedal opening. For a given vehicle power, the battery assist power is determined by considering the battery SOC. The rest of the required power is delivered by the fuel cell stack.

The following equation is proposed to determine the battery assist power P_{assist} by considering the battery SOC.

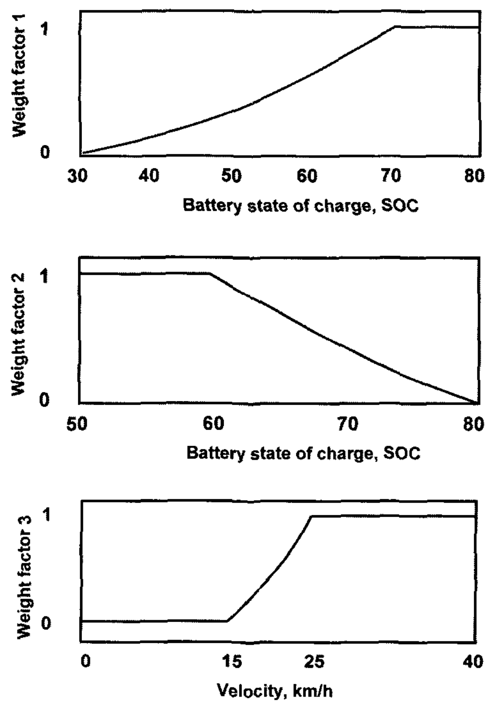

Figure 2. Weight factors of power assist algorithm.

$$P_{assist} = W_1(SOC) \times P_{peak} \quad (1)$$

where W_1 is the weight factor which is a function of the battery SOC and can be used to determine the amount of power drawn from the battery and P_{peak} is the battery peak power. The battery discharge can be managed by Equation (1), which maintains the SOC above the bottom limit.

In the deceleration mode, regenerative braking is involved. In regenerative braking, the regenerative braking torque T_{regen} is controlled by the following equation.

$$T_{regen} = W_2(SOC) \times W_3(V) \times T_m \quad (2)$$

where W_2 and W_3 are the weight factors, each of which determines the amount of regenerative braking according to the battery SOC and the velocity, respectively, T_m is the regenerative torque available at a given motor (generator) speed. Equation (2) prevents the battery from overcharging and provides the driver a comfort feeling at low speed braking. When the battery SOC is not recovered by regenerative braking only, the fuel cell charged battery. Figure 2 gives a set of weight factors adopted in the study.

2.2. Load Leveling Algorithm

In the load leveling algorithm, the fuel cell stack is controlled to be operated in the high efficiency region.

Figure 3 shows the operation strategy of the load leveling algorithm. The load leveling region is selected between [P_{lower} and $P_{optimal}$] and [over P_{upper}]. If the required vehicle power is between P_{lower} and $P_{optimal}$, the fuel cell stack is operated at $P_{optimal}$ and the extra power is used to charge the battery. When the required vehicle power is less than P_{lower}, the vehicle is propelled only by the battery since the fuel cell efficiency below P_{lower} is poor. If the vehicle power is larger than P_{upper}, the fuel cell stack is operated at P_{upper} and insufficient power is supplied by the battery. Therefore, the fuel cell can be operated in the relatively high efficiency region. In the load leveling algorithm, the battery can be charged or discharged

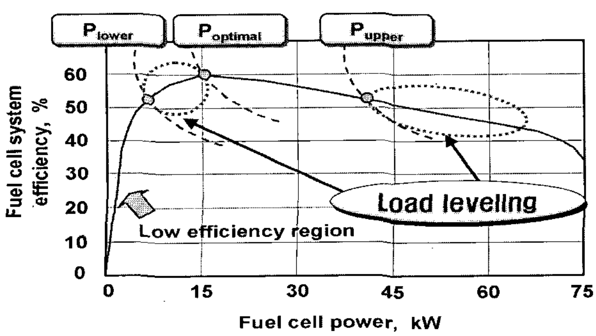

Figure 3. Load leveling operation algorithm.

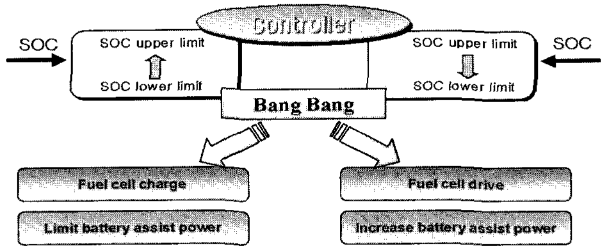

Figure 4. SOC management by bang-bang control.

frequently and this may cause overcharge or over-discharge of the battery, which results in the decreased battery life and fuel efficiency by considering the efficiency of the charge and discharge process. In the study, in order to prevent the battery from the overcharge or over-discharge, a bang-bang control is proposed. The bang-bang control maintains the battery SOC within the pre-determined level.

In Figure 4, a battery SOC management algorithm is shown. The battery SOC is maintained between $SOC_{lower\ limit}$ and $SOC_{upper\ limit}$ by the bang-bang control.

2.3. Equivalent Fuel Algorithm

The equivalent fuel algorithm assumes that the electrical power flow to/from the battery can be represented as an equivalent fuel (Kim *et al.*, 1999; Zeolch *et al.*, 1998). From the equivalent fuel algorithm, distribution of the fuel cell power and the battery power is determined to minimize the fuel consumption for a given battery SOC and a required vehicle power.

In Figure 5, power flow of the FCHEV is shown for charge and discharge. From Figure 5, the required motor power P_{m_req} is represented as

$$P_{m\_req} = P_{fc} - P_{b(c)} \text{ at charge} \quad (3)$$

$$P_{m\_req} = P_{fc} + P_{b(d)} \text{ at discharge} \quad (4)$$

where P_{m_req} is the required motor power, P_{fc} is the fuel cell power, $P_{b(c)}$ is the charge power at the DC/DC input side and $P_{b(d)}$ is the discharge power at the DC/DC output side.

From Equations (3) and (4), the net equivalent fuel

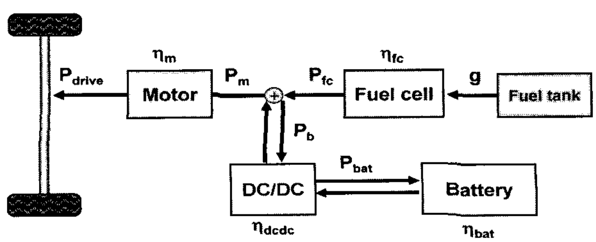

Figure 5. Power flow in a FCHEV.

consumption at charge/discharge, is obtained as

$$\dot{m}_e = \dot{m}_{fc} - P_{b(c)} \times E_{b(c)} \times \eta_{dcdc(c)} \times \eta_{bat(c)} \text{ [kg/s] at charge} \quad (5)$$

$$\dot{m}_e = \dot{m}_{fc} + \frac{P_{b(d)} \times E_{b(d)}}{\eta_{dcdc(d)} \times \eta_{bat(d)}} \text{ [kg/s] at discharge} \quad (6)$$

where $\dot{m}_e$ is the net equivalent fuel consumption, $\dot{m}_{fc}$ is the hydrogen usage, $E_{b(c)}$ is the battery equivalent fuel consumption at charge, $E_{b(d)}$ is the battery equivalent fuel consumption at discharge, $P_{b(c)}$ is the charge power at the DC/DC input side, $P_{b(d)}$ is the discharge power at the DC/DC output side, η_{dcdc} is the DC/DC converter efficiency and η_{bat} is the battery efficiency. In this study, it is assumed that the efficiencies of the battery and DC/DC converter are constant.

The equivalent fuel algorithm is focused on determining the optimal power distribution of the fuel cell and battery to achieve the minimum fuel consumption for various levels of the vehicle power and the battery SOC. Now, we need to obtain the battery equivalent fuel consumption $E_{b(c)}$ and $E_{b(d)}$ at every moment. The battery equivalent fuel consumption $E_{b(c)}$ at charge can be obtained at every moment when the battery is charged by the fuel cell stack.

Equivalent fuel consumption $E_{b(d)}$ at discharge can be considered as an average of the stored energy which is charged by the fuel cell. This, however, requires predetermined information on the amount of charge at every moment for unknown driving cycles, which seems to be almost impossible. Therefore, in this study, it is assumed that the battery charge is carried out at the point where the fuel cell efficiency is high. This assumption is reasonable since nobody wants to operate the fuel cell stack on low efficiency region when charging the battery from the viewpoint of global efficiency of the FCHEV. The fuel cell operation range at charge is selected between the power P_{upper} and P_{lower} in Figure 2. Now, the equivalent fuel consumption $E_{(b)d}$ at discharge is determined as an average of the fuel consumption in the selected operation range.

In order to maintain the battery SOC, the battery

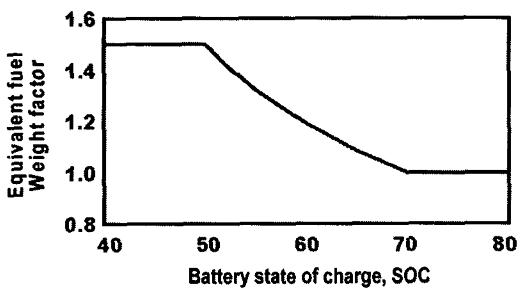

Figure 6. Weight factor for battery management.

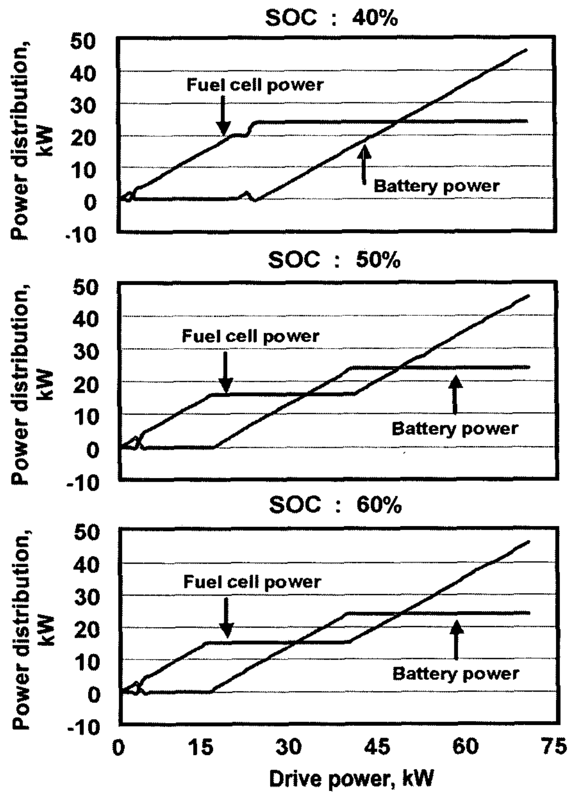

Figure 7. Optimal power distribution.

discharge needs to be controlled. This can be achieved by introducing a weight factor which is shown in Figure 6. By introducing the weight factor, the amount of battery discharge can be controlled. For instance, when the battery SOC becomes low, the equivalent fuel weight factor can be set as large, which limits the application of the battery because the battery equivalent fuel consumption is high. On the contrary, when the battery SOC becomes high, the equivalent fuel weight factor becomes small, which promotes the application of the battery.

Using Equations (5), (6) and Figure 6, the optimal distribution of the fuel cell and battery power can be determined, which minimizes the net equivalent fuel consumption for various levels of the battery SOCs. Figure 7 shows the optimal distribution of the fuel cell and the battery power with respect to the demanded vehicle power for the battery SOC of 40–60 percent. The optimal distribution of the fuel cell and battery power is obtained as follows: for the given battery SOC and required vehicle power, the net equivalent fuel consumption is calculated for different sets of the fuel cell and battery power. This procedure is repeated until the minimum net equivalent fuel consumption is obtained for the given vehicle power. The same procedure is carried out in an iterative manner for various SOCs. As shown in Figure 7, for the battery SOC of 40 percent, the battery takes charge of the vehicle operation only after the vehicle power exceeds 26 kW since the equivalent fuel consumption is relatively large (Figure 6). As the battery SOC increases, the power portion of the battery increases and the fuel cell power decreases since the equivalent fuel consumption of the battery becomes smaller from Figure 6. As for the battery SOC 60 percent, it is seen that the battery power portion increases to the low level of the demanded vehicle power down to 15 kW. It is noted that it is better to use the battery power for the low vehicle power level, 0–5 kW since the fuel cell efficiency is very low for those power levels. In actual driving, the distribution of the fuel cell and the battery power is carried out according to the drive pedal opening and look-up table based on Figure 7.

3. FCHEV SIMULATOR

Figure 8 shows the FCHEV performance simulator developed using MATLAB SIMULINK. The simulator consists of the fuel cell stack, battery, motor, DC/DC converter, vehicle, brake and tire module. Each module is constructed based on the dynamic model obtained.

3.1. Fuel Cell Stack

The PEM fuel cell stack consists of 280 cells and is capable to produce maximum of 75 kW. Performance of fuel cells is affected by the membrane, electrode, cell design, stack temperature, inlet pressure of hydrogen and oxygen. In this study, it is assumed that the pressure is constant at atmospheric pressure.

The stack voltage is defined as the sum of three terms, namely activation polarization, ohmic polarization and concentration polarization (Larminie *et al.*, 2000). The relationship of current and voltage is expressed in the following equations.

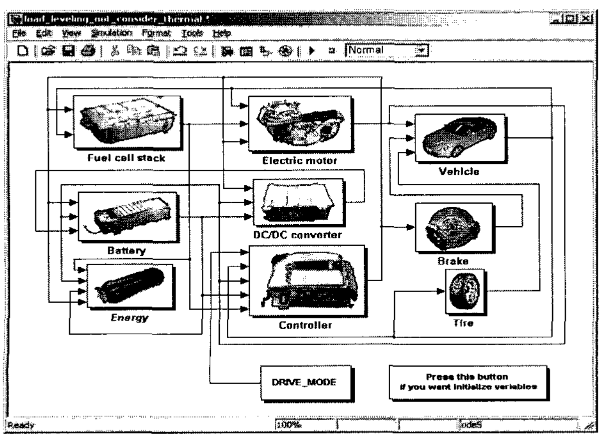

Figure 8. FCHEV performance simulator.

$$V(t)_{cell} = N_{cell} \times (E_{cell} - V_{activation} - V_{ohmic} - V_{concentration}) \quad (7)$$

where $V(t)_{cell}$ is the stack voltage, N_{cell} is the number of cells in the stack, E_{cell} is the open circuit voltage, $V_{activation}$ is the activation polarization, V_{ohmic} is the ohmic polarization and $V_{concentration}$ is the concentration polarization. The amount of hydrogen flow to the stack is related to the current i drawn by the load.

$$\dot{m}_{H_2} = 2.02 \times 10^{-3} \times \frac{1}{2F} i(t) \times N_{cell} \text{ [kg/s]} \quad (8)$$

The actual amount of hydrogen usage can be obtained by considering the fuel cell stack efficiency.

3.2. Traction Motor

The maximum motor torque is dependent on the system voltage and motor speed (Hauer *et al.*, 2000). The desired motor current $i_{desired}$ to generate output torque T_m is expressed as

$$i_{desired} = \frac{T_m \times \omega_m}{V_{bus} \times \eta_{motor}} \quad (9)$$

where V_{bus} is the system voltage, η_{motor} is the motor efficiency.

3.3. Battery

The input and output current of the battery and the SOC are calculated using the battery internal resistance model. The internal resistance is obtained from the experiments with respect to the battery SOCs. The battery voltage is represented as

$$U_a = E - i_a R_i \text{ at discharge} \quad (10)$$

$$U_a = E + i_a R_i \text{ at charge} \quad (11)$$

where U_a is the battery voltage, E is the electromotive force, i_a is the battery current, R_i is the internal resistance.

The battery power is expressed as a function of voltage and current.

$$P_{battery} = E \times i_a - i_a^2 R_i \quad (12)$$

The battery current at discharge can be obtained from the electromotive force, internal resistance and battery power required to drive the motor as

$$i_{battery\ discharge} = \frac{E - \sqrt{E^2 - 4R_i P_{battery}}}{2R_i} \quad (13)$$

The battery current at charge can be obtained in a similar fashion. The battery SOC is directly related with the battery capacity

$$Q_u(i_a, t, \tau) = Q_r(\tau, i_a) - \int_0^t i_a(t)dt \quad (14)$$

where Q_u is the temporary usable capacity which is a function of the current i_a, temperature τ and time t, Q_r is the accumulator's capacity. The integral term in Equation (14) is the usable charge, which has been drawn from the accumulator. In this study, it is assumed that the temperature is constant.

3.4. DC/DC Converter

The DC/DC converter decouples the battery voltage from the system voltage and allows the fuel cell system to operate at a steady state independent from the battery voltage (Goodarzi *et al.*, 2002). The efficiency of the DC/DC converter when sourcing and sinking depends on the power and voltage ratio.

4. SIMULATION RESULTS

Figure 9 through 11 show the simulation results for three operation algorithms. Simulations are performed for federal urban driving schedule (FUDS). In the simulation, the initial condition of the battery SOC is assumed to be 70 percent. In Table 1, vehicle parameters used in the simulation are shown.

In Tables 2 and 3, the drive energy, hydrogen consumptions and battery charge energy obtained from the simulation for FUDS are compared for the three operation algorithms.

Table 1. Vehicle data.

Fuel cell stack (PEM)	Maximum power Fuel type Number of cells	75 kW Hydrogen 280
Motor (AC)	Peak power Rated speed Maximum torque	60 kW 3600 rpm 160 Nm
Battery (Ni-MH)	Capacity	6.5 Ah, 40 modules
Vehicle	Mass Tire radius Frontal Projection area Reduction gear ratio	FCEV : 1850 kg FCHEV : 1900 kg 0.343 m 2.39 m^2 10.03 : 1

Table 2. Drive energy and hydrogen consumption.

	By fuel cell (kJ)	By battery (kJ)	H_2 consumption (kg)
Power assist	6532	1366	0.1452
Load leveling	7056	1682	0.1561
Equivalent fuel	6591	1401	0.1443

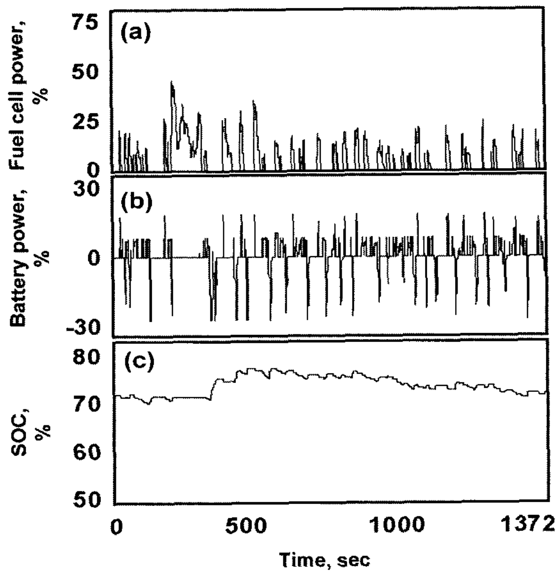

Figure 9. Simulation results for power assist algorithm.

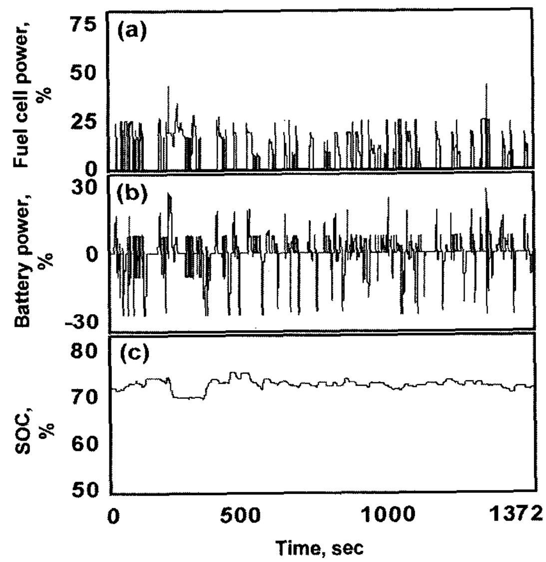

Figure 10. Simulation results for load leveling algorithm.

For the power assist algorithm (Figure 9), it is noted that the vehicle is propelled mostly by the fuel cell (Table 2). The battery power in Figure 9(b) shows a positive value when the battery is used to assist the fuel cell and shows a negative value during the regenerative braking. The battery SOC(c) decreases from the initial SOC while the battery assists the fuel cell in the acceleration mode and increases during the regenerative braking. The battery SOC changes around the initial value, 70 percent. The battery SOC management is carried out by the motor usage weight factors as shown in Figure 2.

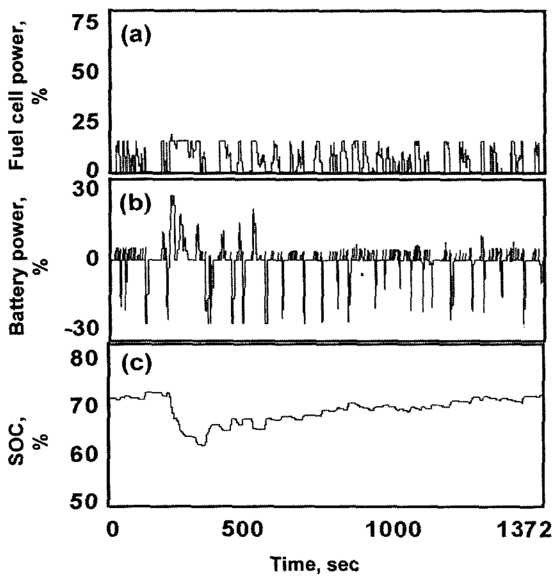

Figure 11. Simulation results for equivalent fuel algorithm.

In Figure 10, simulation results for the load leveling algorithm are shown. It is seen from Table 2 that the fuel cell drive energy is the largest and the battery drive (discharge) energy is the largest among the three algorithms. The frequency and magnitude of the battery discharge (+) and charge (–) increase according to the load leveling algorithm. The battery SOC is maintained within the predetermined range by the bang-bang control.

In Figure 11, simulation results for the equivalent fuel algorithm are shown. The fuel cell stack is operated mostly around 15 kW range where the efficiency is relatively high since the power distribution between the fuel cell and the battery is carried out to achieve the minimum consumption of the equivalent fuel.

From Table 2, it is noted that the hydrogen consumption by the equivalent fuel algorithm is the smallest even if the fuel cell drive energy and battery discharge energy are slightly larger than those by the power assist algorithm. This is because the fuel cell stack is operated at relatively higher efficiency region for the equivalent fuel algorithm.

In Figure 12, both fuel economy and the final battery SOC level are compared for each of the three operation algorithms. These simulation results are obtained for FUDS. It is seen from Table 2 that the load leveling algorithm shows the worst fuel economy among the three algorithms in spite of the smallest fuel cell drive energy. The reason is explained as follows: as shown in Table 3, the regenerative braking energy for each algorithm is almost the same. However, the amount of the fuel cell charge energy (Table 3) and the battery discharge energy (Table 2) by the load leveling algorithm are the largest,

Table 3. Battery charge energy. (kJ)

	By regenerative braking	By fuel cell	Total energy charged at battery
Power assist	1897	81	1978
Load leveling	1898	485	2383
Equivalent fuel	1897	82	1979

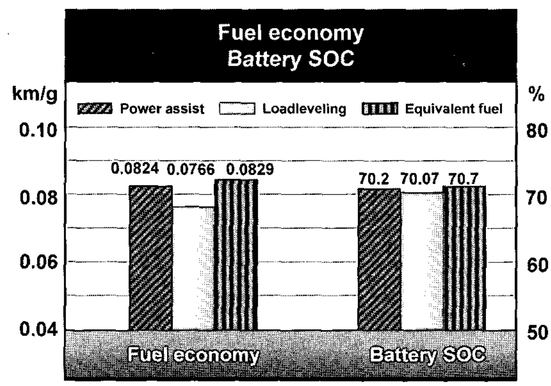

Figure 12. Comparison of fuel economy and battery SOC for various operation algorithms.

respectively among the three algorithms, which results in the worst fuel economy due to the efficiency of the charge and discharge process. The fuel economy of the equivalent fuel algorithm shows the best result among the three algorithms even if the difference is not much compared to that of the power assist algorithm. Considering the fuel economy and the battery SOC, it is found that the equivalent fuel algorithm suits best to the FCHEV investigated in this study.

5. CONCLUSION

Operation algorithms are proposed for a fuel cell hybrid electric vehicle (FCHEV) and FCHEV performances are evaluated using the algorithms. In the power assist algorithm, the battery is used to assist the fuel cell which provides the primary power source. In the load leveling algorithm, the fuel cell is controlled to be operated in relatively high efficiency region while the extra (insufficient) power is managed to charge (discharge) the battery. In the equivalent fuel algorithm, the electric energy stored in the battery is considered to be an equivalent hydrogen fuel. To calculate the equivalent fuel, an equivalent hydrogen fuel consumption for the electric energy is proposed, and a weight factor is introduced to maintain the battery SOC level. From the equivalent fuel algorithm, distribution of the fuel cell and the battery power is determined which minimizes the fuel consumption for a given battery SOC and a required vehicle power. In order to evaluate the performance of the operation algorithm suggested, a FCHEV performance simulator is developed using MATLAB SIMULINK. It is found from the simulation results that the fuel economy and the final battery SOC of the FCHEV depend on the battery discharge energy and it is the best way to maximize the recuperation energy by the regenerative braking to increase the fuel economy for the FCHEV used in this study.

ACKNOWLEDGEMENT–This work was supported by the Brain Korea 21 project in 2003. Also, the authors are grateful for the cooperation by Fuel Cell Team in the Hyundai Motor Company.

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