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FUEL ECONOMY IMPROVEMENT FOR FUEL CELL HYBRID ELECTRIC VEHICLES USING FUZZY LOGIC-BASED POWER DISTRIBUTION CONTROL

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ABSTRACT–This paper presents a new type of fuzzy logic-based power control strategy for fuel cell hybrid electric vehicles designed to improve their fuel economy while maintaining the battery's state of charge. Since fuel cell systems have inherent limitations, such as a slow response time and low fuel efficiency, especially in the low power region, a battery system is typically used to assist them. To maximize the advantages of this hybrid type of configuration, a power distribution control strategy is required for the two power sources: the fuel cell system and the battery system. The required fuel cell power is procured using fuzzy rules based on the vehicle driving status and the battery status. In order to show the validity and effectiveness of the proposed power control strategy, simulations are performed using a mid-size vehicle for three types of standard drive cycle. First, the fuzzy logic-based power control strategy is shown to improves the fuel economy compared with the static power control strategy. Second, the robustness of the proposed power control strategy is verified against several variations in system parameters.

KEY WORDS : Fuel cell hybrid electric vehicles, Power distribution control, Fuzzy logic

1. INTRODUCTION

In forty years, if projections are correct, our lives will have drastically changed. Dwindling oil reserves will dictate our lifestyle adaptations. However, these changes may happen sooner than expected. Recent US actions include canceling ZEV (Zero Emission Vehicles) mandates and shifting to low mileage SUVs. Moreover, the explosive growth of China's manufacturing economy has accelerated the consumption of oil and introduced a new urgency to the search for alternatives to oil dependence.

Hybrid electric vehicles (HEVs) and fuel cell electric vehicles (FCEVs) have been researched to resolve the problems of oil depletion, environmental pollution, and global warming. Recently, HEVs and FCEVs have started to move from the research and development stage to the marketplace. In the past few years, several commercial HEV models, powered simultaneously by batteries and fossil fuel, have taken their place in the mainstream automobile market. Some HEV drive trains have been successfully used in heavy-duty trucks, buses, and military vehicles (Matsumoto *et al.*, 2002; Jung *et al.*, 2003). FCEVs use a fuel cell system, which functions by converting hydrogen into electricity, as the main power source to operate the motor. It has many advantages compared with ICVs and HEVs in that it uses alternate energy sources, is classified as a ZEV, and manages high well-to-wheel fuel efficiency. However, it also has some disadvantages such as a slow response time and low fuel efficiency in the low power region.

In HEVs, the battery system, which is used as an additional power source, assists the internal combustion engine to operate in the high-efficiency region and stores regenerative braking energy when the vehicle is in deceleration mode. Similarly, the FCEV can use additional power sources such as a battery or ultra capacitor to improve its fuel economy and acceleration performance despite the additional cost, weight, and complexity. This type of vehicle is called a fuel cell hybrid electric vehicle (FCHEV). This hybridization of power sources makes it possible to improve the fuel economy. However, a power distribution control strategy is required to determine which proportion of the requested power should be assigned to the fuel cell and which to the battery systems.

Research results from power distribution control strategies for HEVs have been published (Rajagopalan *et al.*, 2003; Baumann *et al.*, 2000; Matheson and Stecki, 2003; Choi and Kim, 2001; Jo *et al.*, 1999; Lee and Sul, 1998), and various types of power control laws are receiving much attention for FCHEVs. A simple static

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**Corresponding author.* e-mail: gm1004@kookmin.ac.kr power distribution control law can adjust the fuel cell current requested according to the threshold value of the battery current and the State Of Charge (SOC) of the battery. In order to develop a more efficient power control strategy, the objective function-based optimal control method and the fuzzy logic-based intelligent method were suggested (Lee *et al.*, 2004; Buie *et al.*, 2004; Oh *et al.*, 2002 b; Choi *et al.*, 2004; Park *et al.*, 2005).

The optimal power distribution control strategy first makes the objective function which describes the fuel consumptions and, second, determines the requested power quantities which will be assigned to each power source based on the minimization of the objective function. This method can also optimize other control parameters such as the battery's SOC, the NVH (Noise, Vibration, and Harshness), and the acceleration performance.

The optimal power distribution control strategy assumes the efficiency characteristics of a dc-dc converter and that of a battery to calculate the optimal power distribution points. However, the efficiency values cannot be accurately estimated, since they vary continuously according to the driving conditions. On the other hand, the fuzzy logic-based power distribution control strategy utilizes the online measurement data to determine the operating point of the fuel cell system. The fuel consumption is minimized at this operating point, while the battery's SOC is maintained at a desired level in the sense of the fuzzy knowledge base. The control performance of the fuzzy logic-based power distribution control strategy is dependent on how well the rule base is constructed from the experimental data for the vehicle system.

In this paper, a static power distribution control strategy (SPDC) and a fuzzy logic-based power distribution control strategy (FPDC) are proposed to improve the fuel economy for FCHEVs. Design concepts are described that enable the fuel cell system to operate in the high-efficiency region for various driving conditions. To demonstrate the validity and performance of the proposed control strategies, some simulations are performed for three standard drive cycles which include urban driving, highway driving, and frequently demanding high-speed conditions. The performance of the FPDC is shown to be more robust than that of the SPDC in the case where the efficiency of the battery varies due to its deterioration.

2. FUEL CELL HYBRID ELECTRIC VEHICLE SYSTEM

2.1. System Configuration

The propulsion energy flow and the information flow of the FCHEV model are shown in Figure 1. The fuel cell system converts hydrogen energy into electrical energy. This electrical energy is then taken and stored in the battery or directly supplied to the electric drive train. 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 state of charge of the battery and of the electric load imposed by the drive train and auxiliaries.

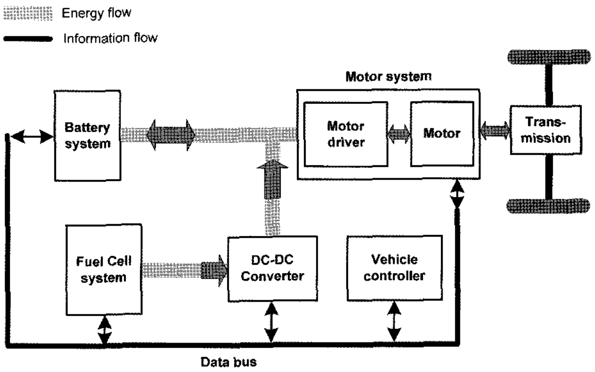


Figure 1. Energy and information flow in FCHEV.

All components communicate via a data bus. The data values involved are: the battery voltage, acceleration pedal position, motor current, battery current, fuel cell stack current, and other variables necessary for the efficient interaction of the components.

2.2. Simulation model of FCHEV

The overall mathematical modeling of the FCHEV consists of the mathematical modelings of several subsystems including the driver, the fuel cell system, the battery system, the motor with transmission, and the vehicle dynamics. The control strategy for the power distribution between the battery and the fuel cell is developed using the simulation model shown in Figure 2 (Hauer *et al.*, 2000, 2001; Hauer and Moore, 2003).

The block 'drive cycle' in Figure 2 provides a function of time which models a typical driving pattern, including acceleration and braking. The block 'Driver' functions as

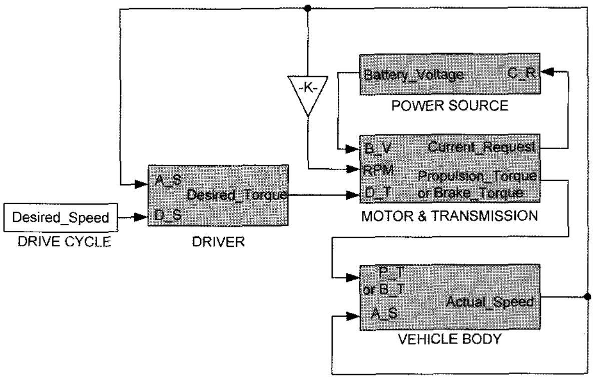


Figure 2. Block diagram of FCHEV.

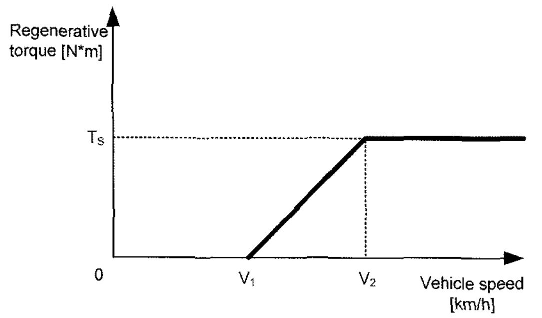


Figure 3. Regenerative braking torque according to vehicle speed (Oh *et al.*, 2002a).

a controller for the vehicle velocity specified in the drive cycle. The block 'motor & transmission' includes the electric motor and the transmission including differential gear system.

In this block, a regenerative braking model is implemented to operate the motor as a generator when the vehicle is decelerated, as shown in Figure 3. The regenerative braking torque is converted into electrical energy and stored in the battery system. Except for the regenerative braking torque, all the braking energy is converted into heat at the brake pads and discs.

The block 'Vehicle body' represents the vehicle's mechanical properties, such as its mass, coefficient of drag, and rolling resistance. The block 'power source' is composed of the fuel cell system, the battery system, and the dc-dc converter. The dc-dc converter boosts the output voltage of the fuel cell system and makes links it with the output voltage of the battery system.

The output voltage of the battery system varies continuously according to the battery's SOC and this voltage is used to calculate the maximum torque of the motor and, thus, the current requested by the motor and transmission block. All other control functions (battery management, fuel cell controller, motor controller, etc.) are assigned to the individual subsystems used to keep the FCHEV in a stable mode.

3. POWER DISTRIBUTION CONTROL STRATEGY

FCHEVs that make use of both a fuel cell system and a battery system have certain technical and economic advantages. The fuel cell is more expensive per watt than the battery, and the battery has advantages in terms of its size and weight, since its power density is higher than that of the fuel cell. In a hybrid engine with fuel cell stacks and a battery, the fuel cell stack normally supplies the rating energy and the battery is used as an auxiliary power supply to satisfy the instantaneous loads imposed by rapid acceleration and ascending roads.

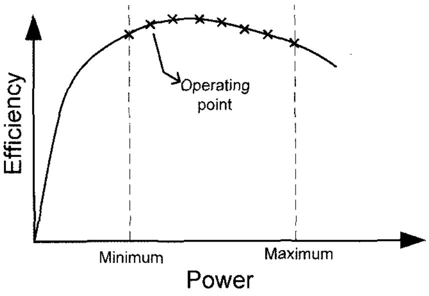


Figure 4. Efficiency curve of a fuel cell system.

The power distribution between the fuel cell and the battery is usually determined by monitoring the power requested for the propulsion of the vehicle and the battery's SOC level. For an efficient power distribution control strategy to increase the fuel economy, the design should incorporate the concept that the fuel cell system has to be operated in the high fuel conversion efficiency region, and the consumption of power stored in the battery system has to be restrained while maintaining the SOC level.

The power stored in the battery system, except for the power due to regenerative braking, all comes from the fuel cell system. The battery is charged mainly by using the surplus power not needed for the propulsion of the vehicle. Since the charging process in the battery system is performed in the form of chemical conversion, the use of battery power is less efficient than the direct use of fuel cell power.

The typical power efficiency curve of a fuel cell can be represented as shown in Figure 4. The efficiency of a fuel cell system is very low during low load operation owing to accessory loads such as the air compressor, hydrogen pump, and water/heat management. Even under high load conditions, the fuel cell is forced to operate with a low power efficiency, since the fuel cell stack voltage drops sharply with increasing load (Hauer *et al.*, 2000).

In the following sections, the SPDC and the FPDC are proposed to improve the fuel economy of an FCHEV; their performances are analyzed through simulations using three driving cycles.

3.1. Static Power Distribution Control

If the fuel cell system is to be controlled so as to operate only at the maximum power efficiency point, the charging and discharging process of the battery should occur very frequently, even when the power required for the vehicle varies only slightly from the point of maximum efficiency. This process results in a large energy conversion loss in the battery, but a trade-off control can be applied by the selection of a few operating points in the high-efficiency region that are indicated as x in Figure 4 (Jeanneret and Markel, 2004).

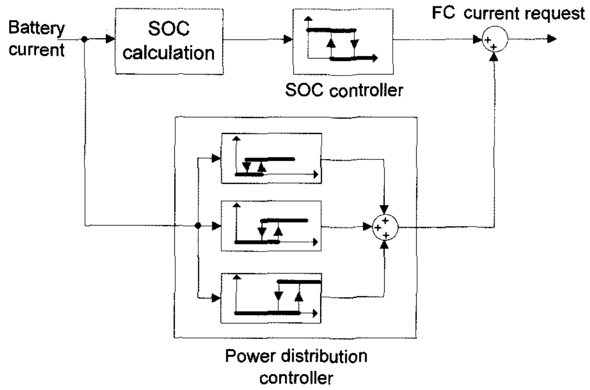


Figure 5. Structure of the SPDC system.

The structure of the SPDC is shown in Figure 5, where the requested value of the fuel cell current is determined by summing the SOC controller output and the power distribution controller output. When the SOC is less than the minimum value, the SOC controller increases the amount of current required from the fuel cell, within the tolerance bound. Making the tolerance bound smaller, which correlates with a smaller dead zone in a relay-type controller, allows for more precise control of the SOC value.

The power distribution controller yields a few levels of current which are combined with the SOC controller to adjust the fuel cell current request. The number of relay-type controllers, the size of the dead zone in each relay, and the magnitude of the output from each relay can be selected based on the electrical parameters of the vehicle and the required performance specifications.

This type of controller can prevent the flow of a large amount of energy from the fuel cell to the battery, such that the fuel cell system may be operated only for some predefined operating points, as shown in Figure 4.

3.2. Fuzzy Logic-Based Power Control

Fuzzy systems are *knowledge-based* or *rule-based systems*. A fuzzy IF-THEN rule is an IF-THEN statement in which some words are characterized by continuous membership functions. The starting point for constructing a fuzzy system is the collection of fuzzy IF-THEN rules from human experts or domain knowledge. The next step is to combine these rules into a single system; however, different fuzzy systems use different principles for this combination.

The basic configuration of a fuzzy system is shown in Figure 6. The fuzzifier is the process of converting crisp values into fuzzy values with membership functions. The rule base represents the collection of fuzzy IF-THEN rules. The fuzzy inference (engine) combines these fuzzy IF-THEN rules into a mapping from fuzzy sets in the input space $U \subset R^n$ to fuzzy sets in the output space $V \subset R$ based on fuzzy logic principles. A defuzzifier is required to convert the resulting fuzzy value into a specific crisp value for the control variable.

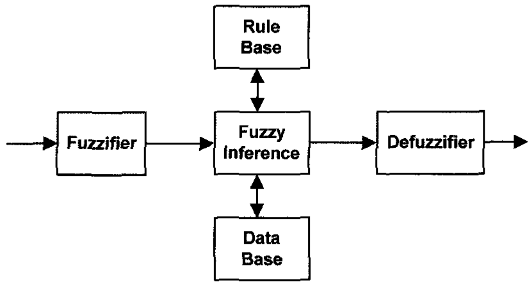


Figure 6. Configuration of a fuzzy logic controller.

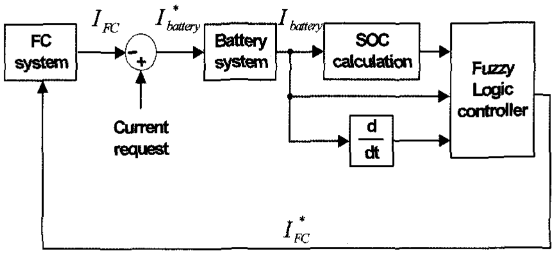


Figure 7. Structure of the FPDC system.

In this paper, the structure of the proposed FPDC is shown in Figure 7 where the fuzzy logic controller yields the current request for the fuel cell based on the fuzzy inputs, the battery current, the derivative of the battery current, and the SOC value. Actually, the fuzzy output is the fuel cell current request (I^*_{FC}).

The membership functions of the fuzzy input and output variables are shown in Figure 8. In the membership functions of the SOC, S, MS, M, MB, and B represent small, medium small, medium, medium big, and big, respectively. For the battery current and the derivative of the battery current, NB, NM, M, PM, and PB represent negative big, negative medium, medium, positive medium, and positive big, respectively. In the membership functions of the fuel cell current request, L, M, H, and VH represent low, medium, high, and very high, respectively.

The rule base of the fuzzy logic controller is constructed based on the following fundamental rules.

R1. If 'SOC' tends to move toward 'S', then I^*_{FC} should go toward 'VH'.

R2. If 'SOC' tends to move toward 'B', then I^*_{FC} should go toward 'L'.

R3. If '$I_{battery}$' and '$d/dt(I_{battery})$' tend to move toward 'NB', then 'I^*_{FC}' should go toward 'L'.

R4. If '$I_{battery}$' and '$d/dt(I_{battery})$' tend to move toward 'PB', then 'I^*_{FC}' should go toward 'VH'.

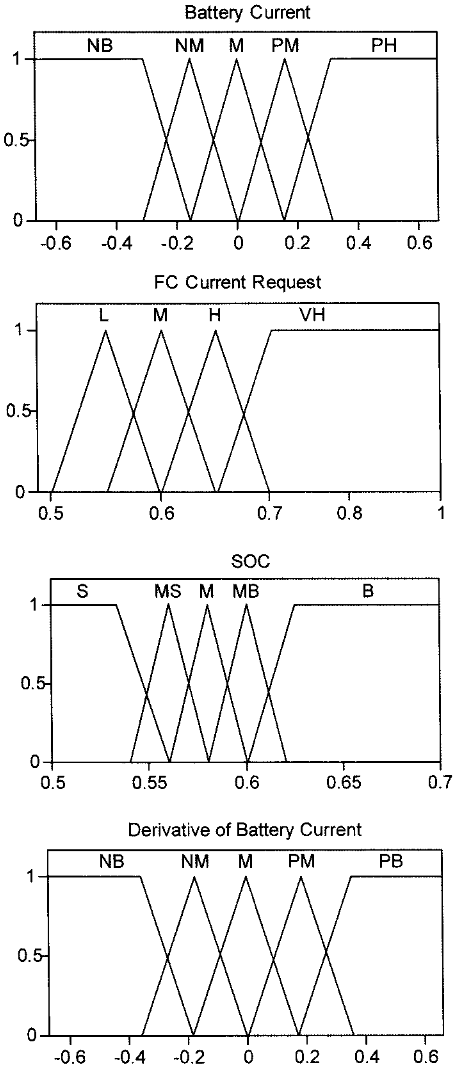


Figure 8. Membership functions of the inputs and outputs of the fuzzy logic controller.

R5. The magnitude of the weight factors for the fuzzy inputs used to determine the output are as follows:

$$SOC > I_{battery} > \frac{d}{dt}(I_{bettery}) \qquad (1)$$

4. SIMULATION RESULTS

4.1. Simulation Parameters

The vehicle parameters selected in this paper are shown in Table 1, where a fuel cell/battery-powered mid-size passenger vehicle is assumed.

The charging/discharging efficiency characteristics of the battery system used herein are represented by equations (2) and (3). During the discharging phase, the efficiency is constant; during the charging phase, it is a function of the SOC (Choi and Kim, 2001).

Table 1. Parameters of the vehicle and its components.

Vehicle:	
Wheel diameter	0.3556 m
Total wheel inertia	4 kg*m^2
Rolling resistance	0.0085
Aerodynamic drag coefficient	0.3
Frontal area	2.00 m^2
Total vehicle mass	1500 kg
Fuel cell system:	
Number of cells	400
Maximum stack current	400A @ 0V;
Voltage current stack characteristic	200A @ 223V See (Hauer *et al.*, 2000).
Battery system:	
Technology	NiMH
Module capacity	22 Ah
Nominal voltage	330V
Transmission:	
Number of gears	1
Total gear ratio	7.51
Electric motor:	
Type	Induction motor
Torque-speed-voltage map	See (Hauer *et al.*, 2000).
Motor inertia	0.1 kg*m^2

$$\eta_{distcharge}=0.95 \qquad (2)$$

$$\eta_{charge}=0.8-0.1SOC^2 \qquad (3)$$

To investigate the fuel economy performance when the battery efficiency characteristics vary due to battery deterioration, etc., the modified battery's efficiency is calculated as in equations (4) and (5).

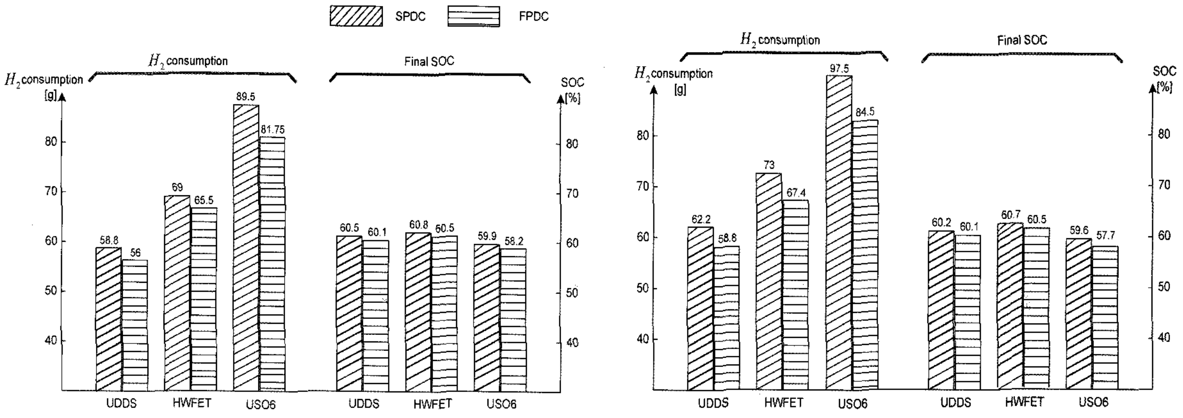
$$\bar{\eta}_{discharge}=0.85 \qquad (4)$$

$$\bar{\eta}_{charge}=0.7-0.1SOC^2 \qquad (5)$$

The efficiency map of the fuel cell system is implemented using a look-up table to calculate the hydrogen fuel consumption. In the simulation model, the peak efficiency of the fuel cell system is 60% at 20 kW and the initial battery SOC is assumed to be 60%.

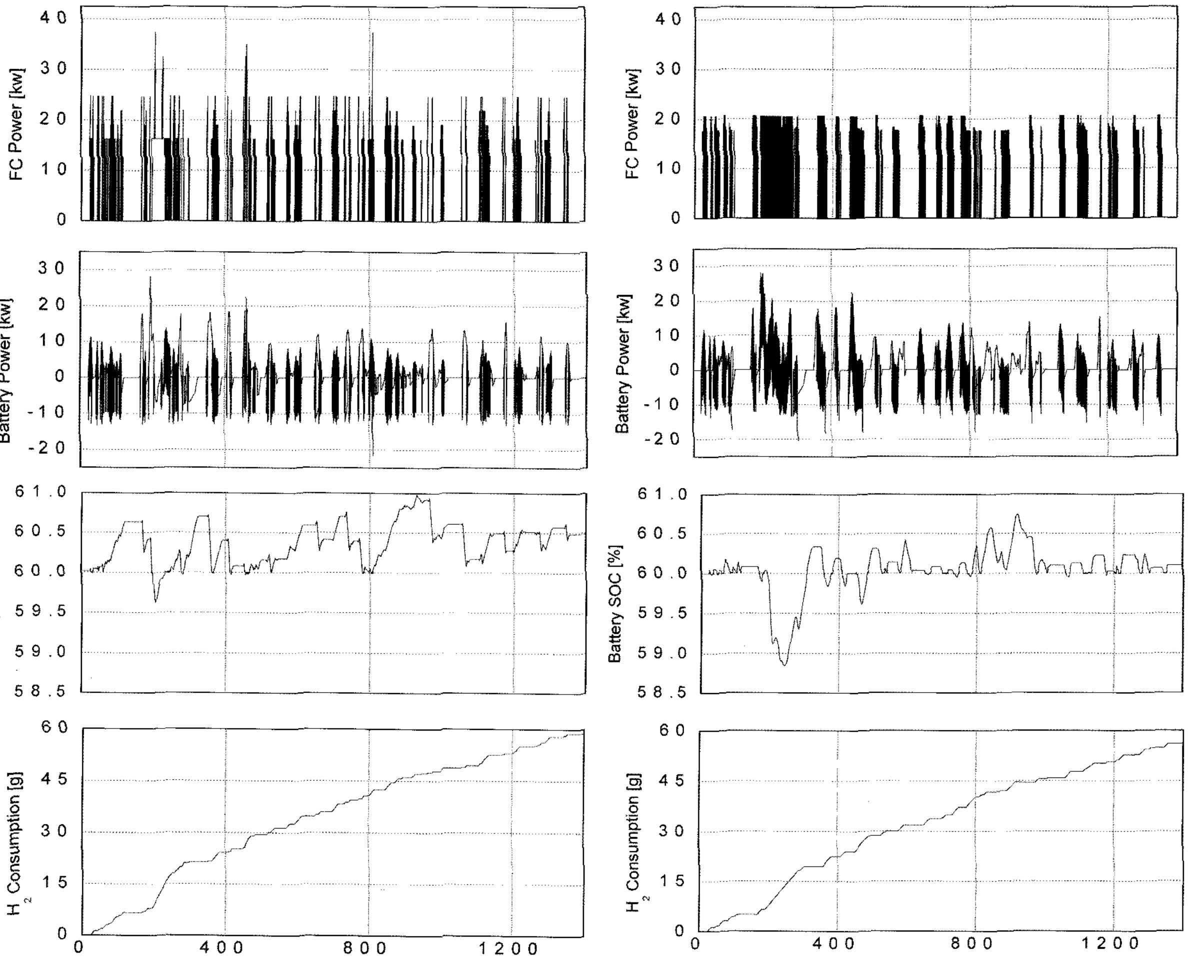
4.2. Simulation Results

For the given three standard drive cycles, simulations were performed using the Matlab/Simulink software based on subsystem models. The three drive cycles are UDDS (Urban Dynamometer Driving Schedule), HWFET (Highway Fuel Economy Test), and US06. These three drive cycles represent city driving conditions, highway driving conditions, and frequently demanding high-speed conditions, respectively.



(a) (b)

Figure 9. Fuel economy of SPDC and FPDC: (a) when battery efficiency is exactly known; (b) when battery efficiency is inexactly known.



(a) (b)

Figure 10. Simulation results for UDDS: (a) when using the SPDC; (b) when using the FPDC.

The relay-type controllers in the SPDC can be easily implemented using programming, but the relay parameters should be well tuned to obtain good fuel economy for the given drive cycle. Four relays are used here for the power distribution controller, where the input battery current is classified into four groups between 5[A] and 30[A] and the output current has four different levels from 0[A] to 80[A].

The dead zone in the power distribution controller is set to 5[A]; however, the dead zone in the SOC controller is set to 0.1[C]. Note that a smaller dead zone generates a more precise response.

In Figures 9(a) and (b), use of either the SPDC or the FPDC successfully controls the battery's SOC for the three drive cycles. However, much less hydrogen fuel is consumed when using the FPDC method, since it searches for the optimum point continuously using the power efficiency curve in Figure 4.

When the battery efficiency characteristics are changed, the fuel consumption increases considerably when using the SPDC with fixed control parameters. On the other hand, the FPDC exhibits a small increase in the fuel consumption compared with the SPDC.

The FPDC is clearly robust when it is applied to the US06 drive cycle. The US06 drive cycle involves a number of large acceleration and deceleration periods and, thus, these drive characteristics may lead to frequent battery charging/discharging operations. This suggests that fuel consumption during use of the FPDC is much reduced compared to the case where the SPDC method is used.

Figures 10(a) and (b) show the simulation results in the case where the SPDC strategy and the FPDC strategy are applied to the UDDS, respectively. The consumed fuel cell power, the battery power, the battery's SOC, and the hydrogen fuel consumption for each control strategy are represented and compared. The FPDC strategy makes the fuel cell system operate near the high power efficiency region and reduces the number of charging and discharging operations in the battery system. This yields an improved fuel economy through the FPDC.

5. CONCLUSION

This paper proposes an SPDC strategy and an FPDC strategy to improve the fuel economy for FCHEVs. The use of battery power is shown to be inefficient compared with the direct use of fuel cell power and, thus, the frequency of the charging/discharging operations of the battery should be reduced. The simulation results show that the FPDC strategy consumes much less hydrogen fuel than the SPDC strategy for the three standard drive cycles. Moreover, the FPDC is robust in the sense that the fuel consumption varies little compared to the SPDC, even when the efficiency characteristics of the battery are changed.

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