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Dual Fuel Cell Mounted FCEV Using Minimum Efficiency based Control Strategy

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Summary

The Fuel Cell Electric Vehicle (FCEV) is getting attention as an eco-friendly vehicle and many studies are actively carried out to improve its fuel efficiency. In this paper, the next generation powertrain of FCEV is introduced where dual fuel cells to improve the operating efficiency are adopted. The system takes the Minimum Efficiency based Control Strategy (MECS) for minimizing the fuel consumption through the distribution of output range between power sources. The simulation results were evaluated for two test cycles, UDDS and HWFET.

Keywords: fuel cell vehicle, powertrain, power management, simulation

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1 Introduction

Conventional Single Fuel cell System (SFS) is configured to operate in the range between 7% and 50% of maximum current, or between inferior power and Maximum Efficiency Power (MEP) [1]. However, this control scheme has two disadvantages. The first is to limit the performance range despite the high power specifications of fuel cell, and the second is that it is not a clear standard for different maximum fuel cell power, so it waste hydrogen by performing the output of the low efficiency area. To address such problems, the Multi-Stack Fuel cell System (MSFS) appeared [3] overcoming the first disadvantage, or a Control Strategy based on Efficiency Map (CSEM) getting over the second disadvantage was proposed [4]. However, solving both of disadvantages at once were not feasible, and thus this research introduces dual fuel cell adopted powertrain to overcome such weaknesses. Since the newly introduced FCEV operates only in the higher efficiency region than the conventional method, the hydrogen consumption can be fully minimized. Section 2 introduces proposed powertrain adopted, Section 3 describes the system dynamics modeling process. The theme of Section 4 is the principle of fuel cell operating section establishment and control strategy and power distribution algorithm. Section 5 presents a way to demonstrate the energy efficiency of the powertrain by converting the electrical energy of battery into hydrogen consumption. Section 6 is simulation results and Section 7 presents conclusion.

2 Proposed Powertrain of FCEV

The proposed powertrain consists of two Proton Exchange Membrane Fuel Cells (PEMFCs) and one Lithium-ion battery. The basic vehicle parameters and information of power sources are listed in Table 1, 2. Most values are tailored to the 2015 model of Tucson ix FCEV of Hyundai Motor [6]. Fuel cells are 75 kW and 25 kW, respectively. The high power fuel cell performs motor drive and battery charging. The high output fuel cell operates as a main power source, the low output fuel cell as a sub power source, the battery as an auxiliary power source and an energy storage device. The total capacity of the fuel cell used in this research is 100 kW. The capacity matching criteria for a system divided into two fuel cells while maintaining the overall system size is the output of the motor and the battery. The size of the main fuel cell was determined to be able to drive an electric motor of 75 kW independently and the remaining 25 kW fuel cell is set to a level suitable for use in place of the 24 kW battery. DC/DC converters have been added to match the voltage between the power sources. Fig. 1 illustrates block diagram of the proposed FCEV powertrain.

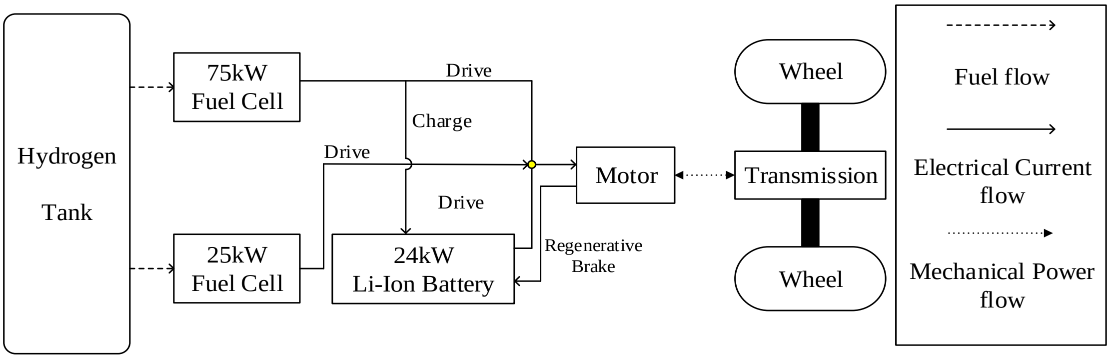


Figure1: Block diagram of proposed powertrain

Table1: Parameters of the vehicle

Item	Value
Vehicle total mass [kg]	1580
Reducer gear ratio	5
Tire radius [m]	0.3015
Rolling resistance coefficient	0.01064
Aerodynamic drag coefficient	0.35
Vehicle frontal area[m^2]	3.0121
Air density [kg/m^3]	1.226

Table2: Powertrain information of FCEV

Component	Value	Type
Electric motor max power [kW]	75	Induction
Stack max power [kW]	100, 75, 25	PEMFC
Fuel cell max efficiency [%]	60	PEMFC
Fuel cell voltage [V]	0.69	PEMFC
Fuel cell max current [A]	500	PEMFC
Fuel cell number [EA]	290, 217, 72	PEMFC
Battery pack capacity [Ah]	60	Lithium-ion
Battery pack max output [kW]	24	Lithium-ion
Battery pack rated voltage [V]	180~206	Lithium-ion
Efficiency of DC/DC converter [%]	95	Boost, Buck/Boost

3 System Dynamics Description

3.1 Motor Required Power

Generally, the vehicle driving force consists of rolling resistance, air resistance, grading resistance, and acceleration resistance. The basic calculation method of each resistance is described in Ref. 4. The required power, P_{req} can be obtained from the torque, T_{mot} and the angular velocity, ω_{mot} of the motor component as shown in Equation (1) [5].

$$P_{req} = \left(T_{mot} \times \omega_{mot}\right) + P_{loss} = V_{bus} \times I_{mot} \tag{1}$$

$$P_{loss} = f\left(T_{mot}, RPM\right) = f\left(T_{mot}, \omega_{mot} \times \frac{60}{2 \times \pi}\right) \tag{2}$$

where P_{loss} is the motor loss power when the motor generates the required power. It is necessary to additionally receive a level corresponding to the loss power from the power sources to meet the required power. This value is determined by the torque and the RPM as shown in Equation (2). The required power can also be expressed as the product of the DC Bus voltage, V_{bus} and the motor current, I_{mot}.

3.2 Fuel cell System Model

When the fuel cell stack is at its maximum output, one cell has a value of 0.65 to 0.75V [2]. Therefore, the cell voltage is set based on an integer value obtained by dividing the voltage at the maximum output of the model. Assuming that the characteristics of the fuel cell, such as maximum current and efficiency, are constant, different output systems can be easily designed by simply setting the number of cells. The fuel cell efficiency is determined according to Equation (3), which can be used to estimate the fuel consumption of the redesigned system. The hydrogen consumption in idle state with 0 kW output was calculated by linear regression method using data values.

$$\eta_{fc} = \frac{V_{stack} \times I_{fc}}{SHV \times \dot{m}_{fc}} \tag{3}$$

$$V_{stack} = V_{fc,cell} \times N \tag{4}$$

Here, η_{fc} is the efficiency of fuel cell, SHV is the specific heating value of hydrogen, 120,000 [kJ/kg]. V_{stack} and I_{fc} are the voltage and current of the fuel cell stack, and $\dot{m}_{fc}$ is the flow rate of fuel consumption. In Equation (4), $V_{fc,cell}$ is one fuel cell voltage and N is the number of cells.

3.3 Battery Model

The fuel cell is inefficient in the low output. Further, since the fuel cell is not an energy storage device but an energy conversion device, energy storage using regenerative braking cannot be performed. Therefore, hybrid system configuration of battery and fuel cell is indispensable to increase fuel efficiency. The battery uses a lithium ion battery with high power density and fast reactivity. The characteristic data of the open circuit voltage, $V_{OCV,cell}$ and internal resistance of the cell, R_{cell} is a function of the State of Charge, SOC [%] and is shown in Fig. 2. Also, the battery performance parameters are following Equation (5) ~ (7) [5].

$$V_{cell} = V_{OCV,cell} - R_{cell} \times I \tag{5}$$

$$V_{bat} = V_{cell} \times N \tag{6}$$

$$\frac{dSOC}{dt} = -\frac{dq}{dt} \times \frac{100}{Q_{bat} \times 3600} \tag{7}$$

where V_{cell} and I is the battery voltage and current, V_{bat} is battery pack voltage and Q_{bat} is the battery capacity [Ah]. q is the charge used by load and when the battery discharges, the direction of the current is negative.

4 Control Strategy

The DFS powertrain can receive power from a total of three power sources. However, not all power sources are used at all times. The control strategy for selecting the power source to be used depends on the required power and the State of Charge (SOC) of the battery. This section describes principle of fuel cell operating range establishment and control strategy for battery charging, respectively.

4.1 Minimum Efficiency based Control Strategy

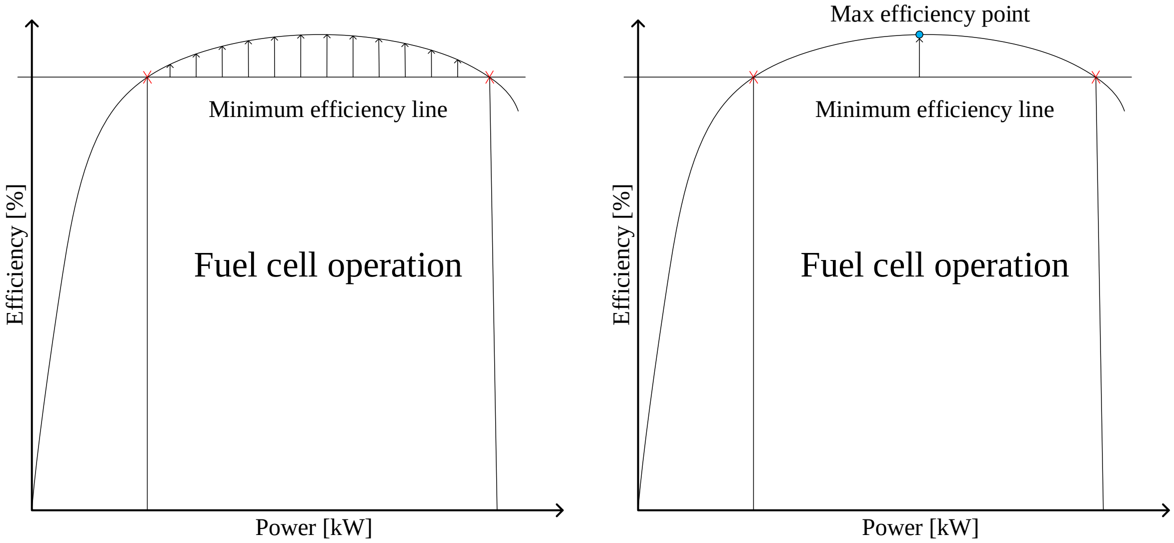
Since the fuel cell efficiency curve is a parabolic shape, the range between the two output power points is determined when the one efficiency point is set like Fig. 2(a). The fuel cell is set to perform power generation only in the efficiency section above the set point. Therefore, this efficiency point is called ‘Minimum Efficiency’. Compared with the conventional operation range of Fig. 1, the output range determined by Minimum Efficiency based Control Strategy (MECS) can be expanded and the average efficiency remains high.

4.2 Non Charging Mode

When the battery is not required to be charged, the main fuel cell and the battery are used as a power source. The sub fuel cell is completely off, eliminating fuel consumption in the idle state. The fuel cell and the battery share the role depending on the operating area determined by MECS like Fig. 2(a).

4.3 Charging Mode

When the battery SOC reaches the lower limit, the thermostatic signal is turns on and charges up to the upper limit (on : 1, off : 0). The power of the sub fuel cell is turned on and in this case, all three power sources are used. The operating range of the sub fuel cell is set by its own MECS. In the charging mode, the output is determined in the order of main fuel cell, sub fuel cell, and battery. If the required power is within the operating range of the main fuel cell, then the main fuel cell will operate at the highest efficiency point as shown in Fig. 2(b). When the required power is higher than the power of maximum efficiency, the hybrid drive mode is performed and satisfied the required power.



(a) Non charging mode (b) Charging mode

Figure2: Main fuel cell operation range

5 Fuel Consumption Evaluation Method

The battery technology has developed dramatically and most of the driving situation can be satisfied even with the auxiliary power source battery alone. In a hybrid system, it is clear that using a battery has a significant impact on fuel economy. Therefore, the energy of all the parts used as the power source must be taken into account in the fuel consumption evaluation of the vehicle. In this paper, we present a new method for converting the battery energy usage to the hydrogen consumption during the cycle period, and evaluates the fuel efficiency using this method.

5.1 GPP Value

The conversion method introduced in this paper is to evaluate whether 1% of the battery has a value of several grams of hydrogen. Estimate the equivalent hydrogen consumption in terms of Grams per Percent (GPP) [g /%]. The GPP value is obtained by extracting the amount of hydrogen used for charging and then dividing by the cumulative amount of the absolute value of the battery change amount as shown in Equation (8). Through this process, we can determine the GPP value during the entire cycle. The amount of charged hydrogen is obtained through the Equations (10), and the output of the battery is converted to hydrogen consumption using Equation (11). The battery SOC change amount is given by Equation (12) [5].

$$GPP = \frac{\int (\dot{m}_{ext})dt}{\int \left(\left| \dot{SOC} \right| \right) dt} \tag{8}$$

$$\dot{m}_{ext} = \dot{m}_{chg} + \dot{m}_{bat} \tag{9}$$

$$\dot{m}_{chg} = \dot{m}_{H_2} - \dot{m}_{drv} - \dot{m}_{aux} \tag{10}$$

$$\dot{m}_{bat} = \dot{m}_{pack} - \dot{m}_{aux,bat} \tag{11}$$

$$\dot{SOC} = \frac{I \times 100}{3600 \times Q_{bat}} \tag{12}$$

$\dot{m}_{ext}$ is extraction value of the hydrogen flow rate that has been or is to be used for charging and is the sum of the values determined by the fuel cell and battery operation. Each flow rate is determined by the equations (10) and (11). Each flow rate value is determined by the ratio of each output for the total output. The total amount of hydrogen consumed in the stack, the amount of hydrogen corresponding to the required power, and the hydrogen consumption for the output of the auxiliary equipment are $\dot{m}_{H_2}$, $\dot{m}_{req}$ and $\dot{m}_{aux}$ respectively. The amount of each hydrogen can be determined as the ratio of each power to the stack power. The hydrogen consumption for the power required for the fuel cell is divided into hydrogen used for driving, $\dot{m}_{drv}$ and hydrogen used for charging, $\dot{m}_{chg}$. The method of converting the power of the battery assumes that the power is generated by the fuel cell. Assuming that the fuel cell generates the corresponding power, the hydrogen flow rate of the auxiliary equipment, $\dot{m}_{aux,bat}$ occurring at that time can also be calculated. Therefore, the hydrogen consumption amount of the battery used for drive, $\dot{m}_{bat}$ is obtained by subtracting the hydrogen consumption amount of the auxiliary equipment, $\dot{m}_{aux,bat}$ from the virtual total system fuel flow amount, $\dot{m}_{pack}$.

5.2 Total Fuel Consumption Calculation

The final battery charge state shows the changed store energy value. More charged energy than the initial state is considered usable in the future. The total fuel consumption, C_{final} is the sum of the amount of hydrogen consumed by the fuel cell, C_{fc} and the energy converted by the battery using the GPP value as shown in Equation (13).

$$C_{final} = C_{fc} + (SOC_{init} - SOC_{final}) \times GPP \tag{13}$$

6 Simulation Results and Discussion

The software used in this research is AMEsim and Matlab/Simulink. The powertrain is designed as AMEsim and the hybrid control unit for the power distribution algorithm designed by Simulink are co-simulated. The simulation was conducted for two test cycles. UDDS and HWFET were selected as typical urban driving cycle and highway driving cycle. As the Thermostatic Control Strategy (TCS) was applied, the initial SOC was selected to be 40, 50, 60% in order to verify the effect of TCS. The total simulated case is six, depending on the cycle and initial SOC. The comparison target is two. Each uses a 100 kW SFS, and is equipped with a TCS and a Power Follower Control Strategy (PFCS).

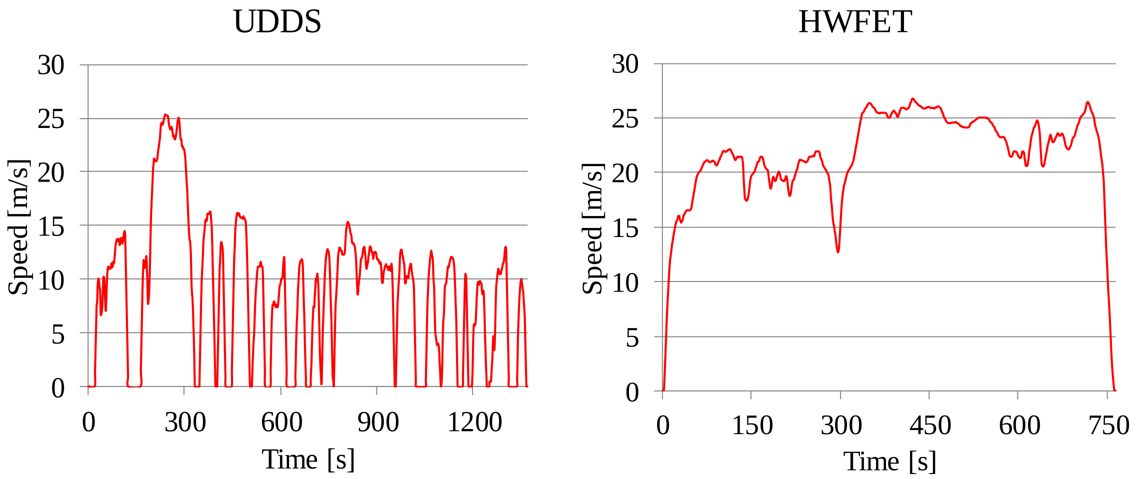


Figure3: Test driving cycles

When the charging of the system is unnecessary, the fuel consumption amount is markedly reduced. This is due to the downsizing effect due to the unused 25kW fuel cell. Even if the system is operating at the same size as the comparators, the fuel consumption is similar or smaller than the target models. This means that there is a potential to improve fuel efficiency through proper tuning of the DFS powertrain and MECS.

7 Conclusion

The research reduced fuel consumption compared to the target models in six test results that changed the initial SOC and test cycles. In the actual driving situation, most of the traveling is performed with the battery fully charged. In this case, since the sub fuel cell is mostly off, fuel reduction through system downsizing can be achieved. Even if the battery needs to be charged, DFS can be said that the overall system is improved because the fuel consumption is less or similar to that of the conventional SFS.

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