한국동력기계공학회지 제21권 제4호 pp. 5-17 2017년 8월 ISSN 1226-7813(Print) ISSN 2384-1354(Online)
Journal of the Korean Society for Power System Engineering http://dx.doi.org/10.9726/kspse.2017.21.4.005
Vol. 21, No. 4, pp. 5-17, August 2017

Regenerative Energy Characteristics of Battery and Supercapacitor in a PEMFC Hybrid System

Byeong Heon Kim*, Qingsheng Wei** and Byeong Soo Oh**†

(Received 31 January 2017, Revised 29 March 2017, Accepted 30 March 2017)

Abstract: This study focuses on the application of the PEM Fuel Cell(PEMFC) hybrid system, which includes a regenerative braking system with supercapacitor(SC) and battery. The purpose of this study is to evaluate the characteristics of regenerative energy and to propose solutions to increase regenerative energy via vehicle simulation. To achieve this target, we set the rated motor speed to 3,000/2,500/2,000 rpm. Because the flywheel is directly connected to the motor, the generator activates regenerative braking by using the rotational momentum of the flywheel when the flywheel reaches the set speed after the motor stops. We could then measure the characteristics of regenerative braking of voltage, current, power, energy change, etc. Meanwhile, we calculate the storage efficiency of the SC or the battery. Our results show that the SC stores 18% of the regenerative energy, while battery stores 15% of the energy. Since the regenerative energy decreases with the decrease of the motor rotating speed that 5,027 J and 2,915 J are restored at 3,000 and 2,500 rpm, respectively. The experimental results also prove that regenerative braking energy is able to be obtained if and only if the speed of flywheel is over 2,500 PRM, and the efficiency of the system can be further improved.

Key Words : Regenerative braking, Energy distribution, Experimental setup, Electrical characteristics, Hybrid vehicle, Efficiency improvement

Nomenclature

η_{regen} : Efficiency of the regenerative braking [%]
$E_{kinetic}$: Kinetic energy of the flywheel [J]
m : Mass of flywheel [kg]
r : Radius of flywheel [m]
V : Voltage [V]
I : Current [A]
$J_{flywheel}$: Inertia moment of the flywheel [kg·m²]
C : Capacitance of the supercapacitor [F]
V_R : Rated voltage [V]
Q : Quantity of electric charge
E_{MAX} : Ideal electrical energy [J]

Greek Symbols

ω : Angular speed of the flywheel

1. Introduction

Fuel Cell Hybrid Electric Vehicles (FCHEV) widely use SCs and batteries in addition to fuel

**† Byeong Soo Oh (corresponding author): Department of Mechanical Engineering, Chonnam National University.
E-mail : bysoh@jnu.ac.kr, Tel : 062-530-1662
*Byeong Heon Kim: Department of Special Equipment, Chunnam Techno University.
**Qingsheng Wei : Department of Mechanical Engineering, Chonnam National University.

cells (Sin, 2005; Paladni et al., 2007; Thounthong et al., 2009; Ehsani et al., 2010) to deal with the positive and negative peak power during instantaneous acceleration and deceleration. Moreover, the regenerative braking system has proven effective in applying instantaneous load to the system, to improve the performance of the fuel cell, and finally, to increase the system efficiency.[1-4)]

The regenerative braking system plays an important role in transforming the kinetic energy of a vehicle into electrical energy. The generated energy is then stored in storage devices such as SCs and batteries, and is reused for driving. This process can improve the vehicle fuel efficiency, especially in urban driving.[5,6)]

Much effort has been made to obtain deep insight into the PEMFC hybrid vehicle. Fernandez et al. investigated the hybrid system performance based on PEMFC and battery, as well as the regenerative braking characteristics of a city train, by employing driving conditions under various modeling assumptions.[7)] Zhang et al. studied the braking energy regeneration control of a hybrid electric bus, which employed fuel cell and Ni-MH battery.[8)] Kim et al. studied regenerative energy using an additional generator and storage in batteries in a PEMFC hybrid system.[9)] However, in these studies the frequent load change and regenerative energy flowing into and out of the battery shortened the battery service life. Meanwhile, thermal energy loss was caused by the chemical storage devices. To compensate for this disadvantage, we use SCs in the present study to obtain regenerative energy. As is well known, SCs can be semi-permanently used as physical storage devices. Compared to batteries, they have advantages of higher power density, higher charge-discharge efficiency, and longer life. SCs can also be charged or discharged rapidly at a high response rate, which makes them significantly effective in regenerative braking. As a result, SCs are preferable for a system that requires high power within a short period of time, and that stores regenerative energy.[3,4,10-15)]

Conventional systems are usually connected to a battery-SC energy storage system by DC/DC converters. Corzine and Ferdowsi improved regenerative energy efficiency by a SC direct connection method.[16)] They employed a complex inverter modulation that allowed the motor drive output voltage to remain steady while the SC had wide voltage variations. An energy storage device was used to broaden the voltage fluctuation range. The regenerative energy was converted from AC to DC by a rectifier and stored in SCs. Since additional converters were not required, decrease in cost and weight could be expected.

Yang et al. proposed an effective method with regenerative braking for a BLDC motor in a light electric vehicle.[17)] The proposed solution achieved dual goals of electric braking and energy regeneration without using any additional converter, SC, or complex winding-changeover technique. In addition, Kim et al. developed a BLDC motor/generator regenerative braking system for a lightweight fuel cell hybrid vehicle.[18)] The above papers used the existing equipped motor to obtain regenerative energy, but the regenerative energy generation efficiency was unsatisfactory. The reason for this is that the coil resistance of the winding inside the motor rotor is large, so a mass of heat forms when energy is regenerated. On the other hand, the coil resistance of the generator rotor windings is small. For this reason, regenerative braking experiments with a generator were conducted to obtain maximum regenerative energy through additional devices.

In this study, we suggest solutions to increase the regenerative energy by using a vehicle simulation equipped with a flywheel. Our experiments started with setting the rotational speed of the motor to

3,000/2,500/2,000 rpm in the PEMFC hybrid system. When the flywheel reached the set speed, the driving motor stopped, and the flywheel energy activated the regenerative braking. To store regenerative energy, we added SCs to the storage system as well as fuel cell and batteries. We used the regenerative energy to understand the characteristics of the regenerative braking system as a function of the voltage, current, power, and energy. We also quantified the storage efficiencies of the batteries and SCs.

2. Experiment

2.1 Development of system

Figure 1 shows a schematic diagram of the PEMFC hybrid system. The Nexa Fuel Cell Power Module, which provides an output of 1.2 kW, served as the main power source. SCs and batteries served as the secondary ones. The SCs offered high power for instantaneous load change, followed by the batteries and fuel cell. The fuel cell charged the secondary power sources according to their states of charge. For the fuel cell, hydrogen was supplied at a pressure of 165 kPa, and air was conveyed at an input temperature of 20°C when the flywheel was forced to rotate. The ESSP-00200F015 model supercapacitors (Enerpulse Technologies, Inc.) were connected in series to achieve a capacity of 15 V, 200 F. GMH100(H) Ni-MH batteries (Global Battery Co., Ltd.) of 12 V, 100 Ah were employed, and connected to two modules in series. Tables 1 and 2 give the specifications of those components.[19] The Ni-MH batteries were capable of dealing with overvoltage when the fuel cell with an operating range 22 V to 36 V was connected in parallel. The NI-PXI 6221 equipment acquired signals from sensors, and its low pass filter eliminated the high frequency noises. The uncertainties of the HANSEN LMS070-04SA12 current sensors we employed were limited to within 1%.

We used a BLDC motor of 1.5 kW, a generator, and a flywheel to obtain the characteristics of the regenerative braking of a small fuel cell hybrid vehicle. Table 3 gives their specifications.

Figure 1 shows that the flywheel was connected to the BLDC motor to store the motor power and transform it into kinetic energy. In the regenerative braking pattern, the flywheel decelerated, and the generator further converted its kinetic energy into electric energy. We can calculate η_{regen} by the following Eq. (1):

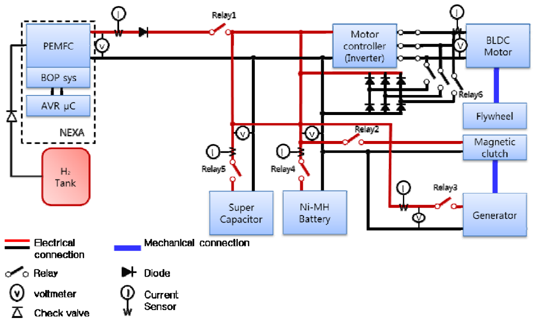


Fig. 1 Schematic diagram of the PEMFC/Ni-MH battery/SC hybrid system and regenerative braking system

$$\eta_{regen} = \left(\int_{brake\_brake}^{brake\_end} v(t) i(t) \right) \Big/ E_{kinetic} \times 100\% \qquad (1)$$

where the kinetic energy of the flywheel $E_{kinetic}$ (Rambaldi *et al.*, 2011) is obtain by:

$$E_{kinetic} = \frac{1}{2} J_{flywheel} \omega^2 \qquad (2)$$

where ω presents its angular speed and the inertia moment $J_{flywheel}$ is expressed as a function of mass m and flywheel radius r, *i.e.*,

$$J_{flywheel} = \frac{1}{2} m r^2 \qquad (3)$$

2.1.1 Electrical characteristic of the battery

The state of charge (SoC) of the battery indicates the percentage of available residual energy relative to the amount of energy when fully charged. In other words, SoC of 100% implies that the battery is fully charged, while a magnitude of 0% indicates that the battery is exhausted. Though it cannot be directly measured, the SoC can be calculated by using various approaches, such as current integration, voltage measurement, specific gravity measurement, and Heuristic method. In this study, we selected the current integration method for its ease of use. However, neither random errors nor system errors are avoidable during measurement. Their accumulation over a long period of time will result in decreased reliability. Therefore, we consider Eq. (4) for SoC determination.[6)]

$$SoC = \left(1 - \int i(t)dt / Q\right) \times 100\% \tag{4}$$

where Q is the quantity of electric charge.

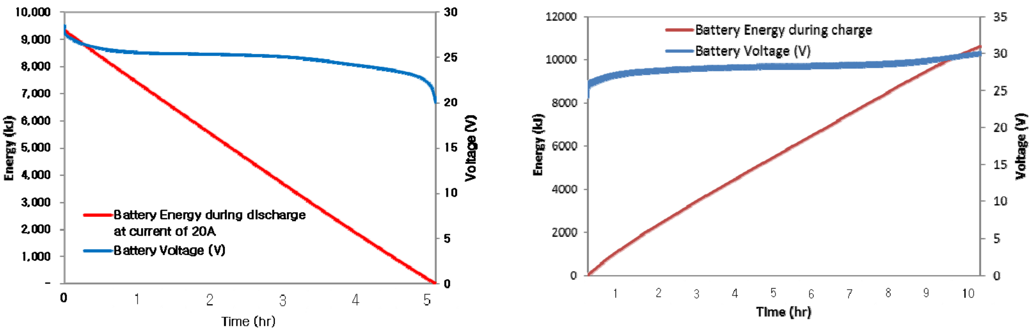
To obtain the Q, we conducted our experiment at ambient temperature (20°C). We set the battery for one-hour relaxation after being fully charged, and then to be consumed at 20 A of 0.2 C_A (current rate, charge or discharge current / rated current).

Figure 2 (a) presents the energy and voltage characteristics when the batteries were discharging at a current of 20 A. The fully charged voltage was 28.5 V at one-hour relaxation after charging, and the total energy obtained discharging from the initial state to the final state with voltage of 20 V was 3,689.105 kJ.

Figure 2 (b) presents the charge characteristics. The maximum voltage in a cell when 100% charged was up to 1.49 V (Sim, 2008). Therefore, we obtain a pause and stabilized voltage of 29.8 V for 20 cells after charging. In addition, the batteries' open circuit voltage (OCV) was 28.5 V.

Table 1 Specifications of the Nexa fuel cell power module and a single GMH100(H) Ni-MH battery module

Nexa Fuel Cell	Rated power	1200 W
	Operating Voltage Range	22 V to 36 V
	Number of Cells	36
	Weight	22 kg
GMH100 Ni-MH Battery	Nominal Voltage	12 V
	Capacity	100 Ah
	Number of Cells	10
	Weight	20 kg



(a) (b)

Fig. 2 Charge-discharge characteristic curve of battery: (a) Characteristics of discharge, and (b) characteristics of charge

Table 2 Specifications of a single SC module

Rated Capacitance, CR (25 °C)		200 Farads
Rated Voltage, VR		15 V
Max. Voltage, VM		16 V
Rated Current (25 °C)		49 A
Max. Current (25 °C)		825 A
Max. Stored Energy (at VM)		25.6 kJ (7.1 Wh)
Specific Energy	Gravimetric	2.96 Wh·kg^{-1}
	Volumetric	2.37 Wh·L^{-1}
Specific Power (at matched load)	Gravimetric	4.28 kW·kg^{-1}
	Volumetric	3.43 kW·L^{-1}
Maximum Internal Resistance(ESR)	DC (100 A)	4.1 mΩ

Table 3 Specifications of the BLDC motor, flywheel, and generator

BLDC Motor	Poles		4
	Phases		3
	Driving		Full Wave
	Position Detection		Hall Generating Detection
	Characteristics without Load	Velocity	4,450 Revolution Per Minute (RPM) ± 10%
		Current	5.5 A ± 10%
	Load Characteristics	Time	Continuous
		Voltage	24 V DC
		Rated Current	66.3 A +10%
		Rated Velocity	3,000 rpm
		Rated Torque	48.7 kg·cm
		Momentary Torque	97.4 kg·cm
	Insulation Voltage		AC 1,500 V 1 min
Flywheel	Weight		16.4 kg
	Diameter		370 mm
	Thickness		20 mm
	Moment of Inertia		0.28 kg·m^{-3}
	Density		7,850 kg·m^{-3}
Generator	Phases		3
	Voltage		24 V AC
	Current		60 A
	Rectification Method		Built-in IC Regulator

2.1.2 Electrical characteristic of the supercapacitor

We determined the capacitance of the supercapacitor C for given rated voltage V_R and quantity of electric charge Q by the following equation:

$$\mathrm{C} = Q/V_R \tag{5}$$

and calculated the ideal electrical energy stored in the SC E_{MAX} as follows (KIST, 2007):

$$E_{MAX} = \frac{1}{2} C V_R^2 \tag{6}$$

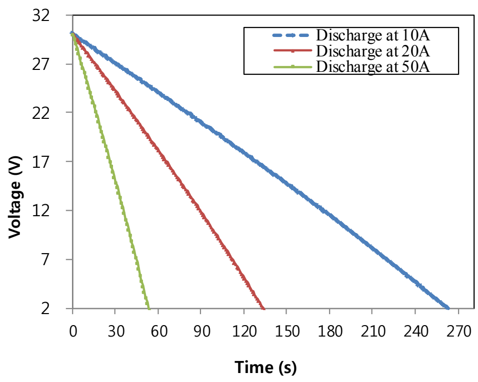
Therefore, we can easily determine the SoC of a supercapacitor SoC_{SC} by voltage measurement, i.e.,

$$SoC_{SC} = \left(V_{SC} / V_{SC,rated}\right) \times 100\% \tag{7}$$

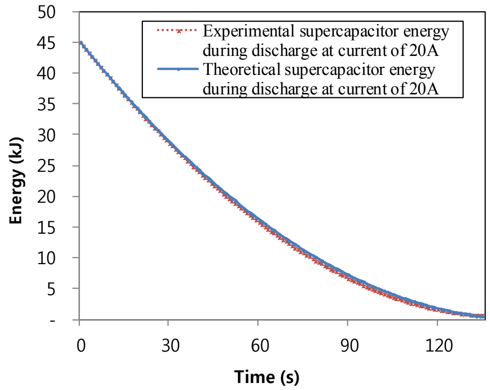
Figure 3 (a) presents the discharge characteristics of the supercapacitor at a constant current of 20 A, which we inspected by experiments. The theoretical energy is 45,000 J at 30 V. At this time, we applied the value of the change in voltage to the experimental data. The experimental energy was 45,057 J. We ignored the energy at less than 2 V. Figure 3 (b) shows the discharge characteristic curves of the SC during discharge at 10 A, 20 A, and 50 A. The voltage decreased linearly at a constant discharge current.[22)]

2.2 Experimental method

The SoC and capacities of batteries and SCs are important factors in regenerative braking. If maintained at 100% of SoC, secondary power sources will probably be damaged by overcharging from the large supply of regenerative energy. In this study, we used a fuel cell, batteries and SCs with hybrid control to run a motor, and to save electrical energy to kinetic energy in a flywheel. First, we set



(a)



(b)

Fig. 3 Discharge characteristic curve of the SC: (a) Variation of energy, and (b) variation of voltage

the speed of the motor to 3,000/2,500/2,000 rpm. We connected the flywheel to the motor, and drove it to rotate the flywheel. Once the flywheel reached the set speed, we shut off the motor, and the energy of the flywheel initiated regenerative braking. We recorded the voltage and current and calculated the power and energy, especially the regenerative braking energy stored in the batteries and SCs.

Conventionally, batteries are used to capture waste energy from braking to increase the efficiency of the HEVs, BEVs, and FCEVs. SCs have also been considered for their fast response speed (0.3 sec to 30 sec) and high power density (10,000 W/kg).[13,21] Typically, regenerative braking is used in a vehicle equipped with a motor. However, though different in design, generators share essentially the same function as motors, i.e., to efficiently output power. Moreover, Kim et al. conducted experiments on regenerative braking with a hybrid power system that consisted of fuel cell, flywheel, motor or generator, and Ni-MH battery.[18] They proved that the generator was more efficient than motor in converting the kinetic energy of the flywheel into electricity. Therefore, in this paper we use fuel cell, generator, flywheel, Ni-MH battery and SC, to save the regenerative braking energy more efficiently and quickly than in the previous study. We measured the storage efficiency of the secondary power sources and the regenerative energy upon regenerative braking using the generator.

Table 4 Test conditions

Content	Value
SoC of Battery	25%, 25.5 *V*
Flywheel Rotating Speed	3,000/2,500/2,000
SoC of Supercapacitor	85%, 25.5 *V*

The current response characteristics of a fuel cell hybrid system vary with different SoCs of secondary power sources. A system without DC/DC converter first loads the power source with higher voltage, and later loads the lower one when their SoCs differ. In addition, due to the different voltage, the power source with the higher voltage first charges the lower one.[5] By these characteristics, the fuel cell system's loading ratio differs, and the times when the fuel cell system charges the secondary power sources also differ. Here, because there is no DC/DC converter among fuel cell system, battery, and SC, we should carefully consider the voltage characteristics when constructing the system.

Table 4 shows the following conditions that we carried out the experiments to identify the various characteristics. We initially set the 25% of the battery SoC at 25.5 V, and the 85% of the SC SoC at 25.5 V to save regenerative energy from the generator. The energy from the batteries and SCs was simultaneously used to run the flywheel to the set speed. Since the generator produced DC electricity from 0 V to 26.5 V, and we did not employ a converter after the generator, the batteries and SC could only directly save the regenerative energy from the generator with output voltage higher than 25.5 V.[23)]

3. Results and Discussion

Figure 4 presents the experimental results with regenerative braking by using the BLDC motor, and shows the characteristics of the fuel cell/battery/SC hybrid system. We set the SoCs of the batteries and SCs to 25% and 85%, respectively. In this regenerative braking experiment, motor speed increased from 0 to 3,000±100 rpm in steps of 1,000±100 rpm within an interval of 60s, and then dropped to 0 after running for 240s. During the process, we collected the voltage, current, output power, and energy characteristics.

Figure 4 (a) presents the voltage change characteristics against the time. At 60s, 120s and 180s, we increased the rotating speed by 1000, and the voltages of fuel cell and battery decreased while the output voltage varied from 23 V to 26 V. Since the maximum regenerative voltage of the motor (19 V) was lower than that of the battery and SC when it gradually decreased, the secondary power source could not store the regenerated energy. Therefore, we installed the regenerative energy storage method with an additional two-way DC/DC convertor, and connected the SC in parallel to lower the voltage.

Figure 4 (b) shows that at the moment that the motor changed from 2,000±100 rpm to 3,000±100 rpm, the SC offered a current of 28 A~43 A within 2s, and soon reduced to 0 A. Subsequently, the

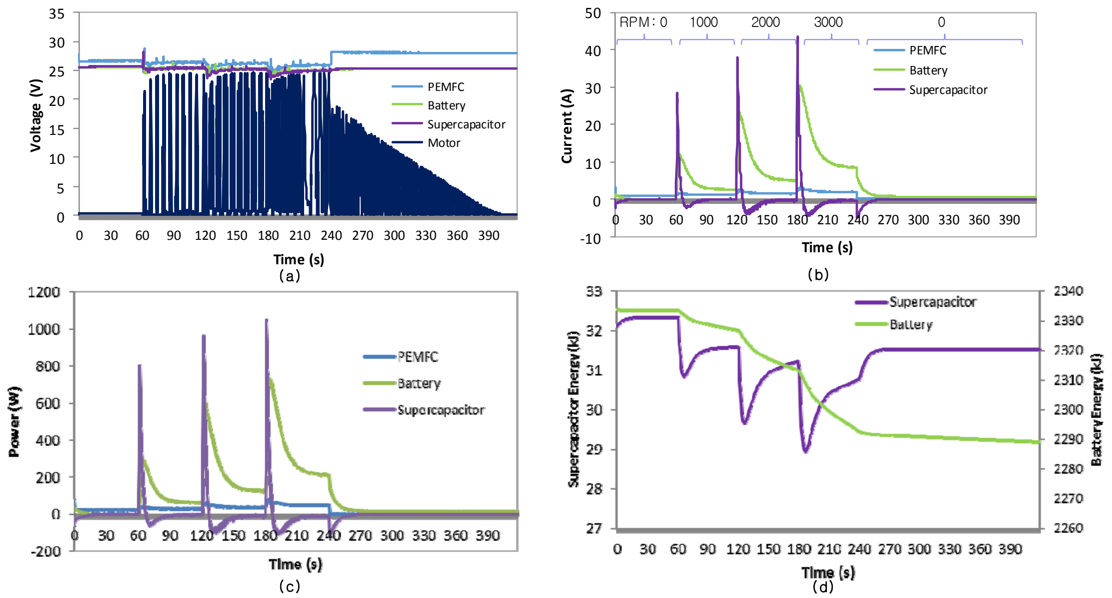


Fig. 4 Regenerative braking energy by using the motor of the PEMFC-Battery-SC hybrid system: (a) Variation of voltage; (b) variation of current; (c) variation of power; and (d) variation of energy

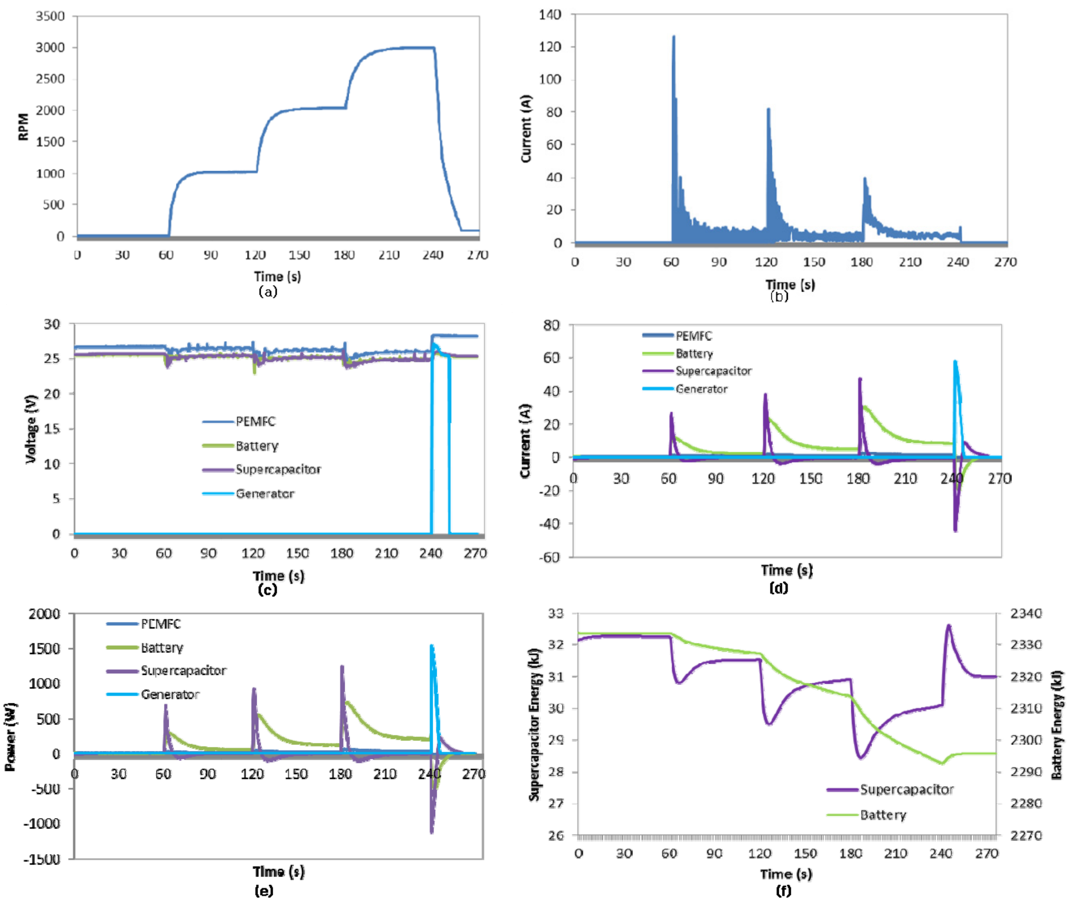


Fig. 5 Regenerative braking energy by using the generator of the PEMFC-Battery-SC hybrid system (battery and SC): (a) Variation of motor rotating speed; (b) variation of motor current; (c) variation of voltage; (d) variation of current; (e) variation of power; and (f) variation of energy

battery and fuel cell were loaded.

The motor current was unable to occur, because the SoC and voltage of the battery and SC were higher than the regenerated voltage of the motor. Therefore, the regenerative energy could not be restored.

At 3,000±100 rpm, both the current load of the battery and that of the fuel cell increased, and the output current remained steady after we held the rotating speed of motor to a constant value.

Figure 4 (c) shows that at a rotating speed of 3,000±100, the maximum output powers of SC, battery and fuel cell at 180s were 1,049 W, 733 W and 80 W, respectively.

We found that the battery’s energy continuously decreased during the motor was driven for 240s, as Fig. 4 (d) shows. The calculated decreased energy rose to 41 kJ. Meanwhile, the SC was repeatedly being charged and discharged, and the decreased energy was 1.3 kJ.

Overall, though the flywheel has kinetic energy of 13.8 kJ, the energy regenerated during regenerative braking was 0 kJ, with regeneration efficiency of 0%.

Figure 5 reveals the characteristics of the fuel cell/battery/SC hybrid system, including the acceleration performance and characteristics of regenerative braking with a generator by the motor output rotating speed.

Initially, we set the SoCs of battery and SC to 25% and 85%. The rotating speed of motor increased in steps of 1,000±100 rpm within an interval of 60s, as well. After the motor rotating speed reached 3,000±100, we activated the generator to bring the regenerative braking energy. At the same time, the regenerative energy was stored in the battery and SC.

Figure 5 (a) displays the motor rotating speed changing characteristics when it varied from 0 to 3,000±100 rpm. Figure 5 (b) shows that during the period 60s to 120s, a current of 120 A was suddenly loaded, and slowly decreased to 18 A as the rotating speed gradually became steady. We observe similar situations at the following two intervals, and the maximum currents of 107 A and 56 A were loaded at the moments around 120s and 180s, respectively. Figure 5 (c) shows that at 60s, 120s and 180s, voltages of fuel cell and battery decreased when the motor rotating speed increased, and the output voltage fluctuated within the range from 23 V to 26 V. Figure 5 (d) presents the current changing characteristics. At the moment that the motor rotating speed increased from 2,000±100 to 3,000±100, the SC provided a current of 9 A~47 A within 3s. After reaching the maximum value of 47 A, the SC current quickly decreased to 0 A. The battery presented a similar reaction at the beginning of the rotating speed change, but a lower maximum current, i.e., 30 A. Moreover, the decline rate was much smaller, and the final current was constrained to a certain value other than 0 A.

Overall, the fuel cell provided power with a maximum current of 2.4 A, and most of the load was placed on the battery. Figure 5 (e) proves that at the beginning of the increase of motor rotating speed, the SC offered the main power, following by the battery and fuel cell. After that, the battery took on the role of being mainly loaded. The maximum output power of the SC, battery and fuel cell were 1,241 W, 694 W and 67 W, respectively. Figure 5 (f) demonstrates the energy changing characteristics through the experiment. At the time that the motor rotating speed increased, the SC's energy was rapidly consumed, which manifested as a sudden energy drop within a few seconds. After that, the SC was charged again, which manifested as energy increasing. Therefore, by 240s, the total amount of energy hadn't changed a lot, with a drop of only 2 kJ. On the other hand, the energy of the battery was continuously consumed, and the total drop amount was 41 kJ.

Table 5 shows the statistics of the storage efficiency of the regenerative energy. We found that when the kinetic energy of flywheel was 13,803J, the regenerative energy of the generator was 5,027 J. Therefore, we calculated the efficiency of regenerative energy by generator to be 36%. During regeneration, the SC stored 18% of the flywheel energy, i.e., 2,512 J. The battery took another 15%, i.e., 2,181 J. The total efficiency of the whole energy storage system was 33%.

Though the battery provided the maximum load power from 1s to 1.4s when the motor rotating speed changed, and stored the power supplied from the regenerative braking devices, the speed of charge moving in and out of the battery remained a problem. Therefore, in order to obtain a higher charge speed, excellent SCs, with in particular high power density, are preferable. Since the coil resistance of the winding inside the rotor is large, a large amount of regenerative energy is transferred into heat. On the other hand, the performance of a generator is superior, because its coil resistance of winding inside is small. The efficiency increased when the generator was used during regenerative braking.

Figure 6 presents the analysis results of energy characteristics at rotating speed of 3,000, 2,500 and 2,000 rpm. We found that the kinetic energy of the flywheel at 3,000 rpm was 13,803 J, and the corresponding regenerative energy was 5,027 J. In this case, the energy stored in the battery and the SC was 4,693 J. The kinetic energy of the flywheel at 2,500 rpm was 9,585 J, and the corresponding regenerative energy was 2,915 J. In this case, the energy stored in the battery and the SC was 2,676 J. The kinetic energy of the flywheel at 2,000 rpm was 6,134 J, and the corresponding regenerative energy was 0 J. The amount of regenerative energy to be generated varies together with the rate of rotating speed, and regenerative energy can be obtained only if the rotating speed is no less than 2,500 rpm. We predict that the efficiency of the system can be improved when the system is driven at 2,500 rpm or more to generate regenerative energy.

Figure 7 compares the energy storage loss rate between the battery and SC when the regenerative energy was stored during regenerative braking by using the generator at 3,000/2,500 rpm. Accordingly, the loss rates were 2% and 1%, respectively, when the kinetic energy of flywheel was regenerated, and stored in single secondary power source, i.e., battery or SC. When both of them were used, the total loss rate was 3%. The loss rate at 2,500 rpm presented the same rate at 3,000 rpm. We can predict that there are similar tendencies in other systems where the loss rates are the same when the regenerative energy is generated.[23)]

Table 5 Storage efficiency of the regenerative energy

Division	Value
Kinetic Energy of the Flywheel	13,803 *J*, 100%
Regenerative Energy by the Generator	5,027 *J*, 36%
Stored Supercapacitor Energy	2,512 *J*, 18%
Stored Battery Energy	2,181 *J*, 15%
Total Stored Energy	4,693 *J*, 33%

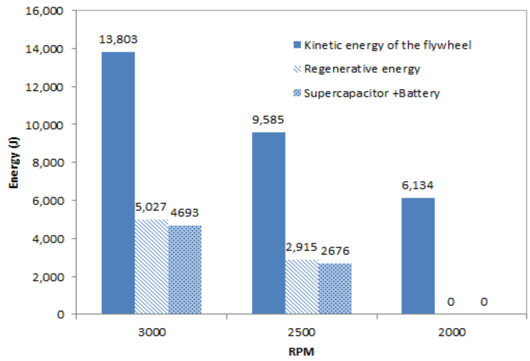


Fig. 6 Analysis of energy by the motor rotating speed

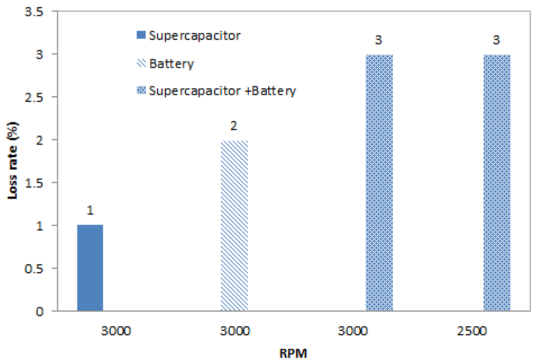


Fig. 7 Comparison of loss rates

4. Conclusion

The continuous development of the fuel cell vehicle market is resulting in regenerative energy being generated along with the rotating speed of flywheel in fuel cell hybrid system. We studied the output power density being recovered as regenerative energy by excellent batteries and SCs when motor and generator were used.

From this study, we can draw the following conclusions. In order to identify the loading characteristics of power source in frequently loaded system, we constructed a fuel cell-battery-SC hybrid system. The output power of the fuel cell system was 1.2 kW, the capacity of a fully charged battery was 2.4 kWh at 24 V, 100 Ah, and the capacity of the SC that provides high output power was 30 V, 100 F. To analyze the energy efficiency of a regenerative braking device with a flywheel, we constructed a system that regenerated energy by using a BLDC motor and generator during regenerative braking, and stored it in batteries and SCs. The motor was nominally 1.5 kW, and the generator provided an output power of 1.4 kW at 24 V, 60 A.

We examined the characteristics of regenerative braking by using a motor. When the motor was used, the regenerative voltage was up to 19 V. However, compared to the voltage of the auxiliary power source, the regeneration voltage was small, and the generative energy could not be stored. Therefore, the storage efficiency was 0%. We predicted that the regenerative energy could be generated and stored when an additional bidirectional DC/DC converter was attached.

Next, we studied the characteristics of regenerative braking by using a generator. During regenerative braking, the regenerative energy that has higher output voltage than the auxiliary power source can be stored. The regeneration efficiency of the generator based on the kinetic energy of the flywheel was 36%. The SC and battery stored 18% and 15% of the regenerative energy within 6s, resulting in a total regeneration efficiency of 33%. The SC proved to have higher regeneration efficiency than the battery. Though the battery was mainly loaded during the whole process and stored the power provided by the regenerative braking device, the speed of electric charge moving into and out of the battery remained a problem. Therefore, in order to obtain a higher charge speed, an excellent SC with in particular high power density is preferred. Since the coil resistance of the winding inside a rotor is large, a large amount of regenerative energy is transferred into heat. On the other hand, the performance of a generator is superior, because the coil resistance of the winding inside is smaller. The efficiency can be improved when a generator is used during regenerative braking.

We inspected the characteristics of regenerative braking by different rotating speed by using a generator. Energy of 5,027 J was regenerated at 3,000 rpm, while 2,915 J was regenerated at 2,500 rpm. The energy stored in battery and SC decreased, because the regenerative energy decreased along with the decreasing of rotating speed. Regenerative braking energy can be obtained only if the rotating speed is at 2,500 rpm or more, and we expect that the system efficiency can be improved when driven under this condition.

Based on the kinetic energy of the flywheel, we compared energy storage loss rates between the battery and the SC at 3,000/2,500 rpm when the regenerative energy was stored during regenerative braking by using a generator. When stored only in battery or SC at 3,000 rpm, the loss rates were 2% and 1%, respectively. When both of them were used, the total loss rate was 3%. The loss rate distributions at 2,500 rpm and at 3,000 rpm were the same. We predict that there are similar tendencies in other systems that generate regenerative energy. The energy storage loss rate of a SC is less than 1%, which is better than that of a battery.

Acknowledgement

The content is partially included in the doctoral thesis by Byeongheon, Kim, Department of Mechanical Engineering, Chonnam National University, 2015.08.

References

1. J. G. Sin, 2005, "Performance Analysis and Optimization of Control Strategy for Fuel Cell

Hybrid Vehicle Using Battery and Ultra Capacitor", Seoul National University.

2. V. Paladini, T. Donateo, A. De Risi and D. Laforgia, 2007, "Super-capacitors Fuel-cell Hybrid Electric Vehicle Optimization and Control Strategy Development", Energy Conversion and Management, Vol. 48, No. 11, pp. 3001-3008.
3. P. Thounthong, S. Rael and B. Davat, 2009, "Energy Management of Fuel Cell/Battery/ Supercapacitor Hybrid Power Source for Vehicle Applications" Journal of Power Sources, Vol. 193, No. 1, pp. 376-385.
4. M. Ehsani, Y. Gao and A. Emadi, 2010, "Modern Electric, Hybrid Electric, and Fuel Cell Vehicles", CRC Press.
5. M. K. Yoong, Y. H. Gan, G. D. Gan, C. K. Leong, Z. Y. Phuan, B. K. Cheah and K. W. Chew, 2010, "Studies of Regenerative Braking in Electric Vehicle", IEEE Conference, pp. 40-45.
6. L. Rambaldi, E. Bocci and F. Orecchini, 2011, "Preliminary Experimental Evaluation of a Four Wheel Motors, Batteries Plus Ultracapacitors and Series Hybrid Powertrain", Applied Energy, Vol. 88, No. 2, pp.442-448.
7. L. M. Fernandez, P. Garcia, C. A. Carcia and F. Jurado, 2011, "Hybrid Electric System Based on Fuel Cell and Battery and Integrating A Single DC/DC Converter for A Tramway", Energy Conversion and Management, Vol. 52, No. 5, pp. 2183-2192.
8. J. Zhang, C. Lv, M. Qiu, Y. Li and D. Sun, 2013, "Braking Energy Regeneration Control of A Fuel Cell Hybrid Electric Bus, Energy Conversion and Management", Vol. 76, pp. 1516-1523.
9. S. H. Kim, O. J. Kwon, D. S. Hyun, S. H. Chun, J. S. Kim, B. H. Kim, S. T. Hwang, J. S. Song, M. T. Hwang and B. S. Oh, 2013, "Regenerative Braking for Fuel Cell Hybrid System with Additional Generator", International Journal of Hydrogen Energy, Vol. 38, No. 5, pp. 8415-8421.
10. P. Sharma and T. S. Bhatti, 2010, "A Review on Electrochemical Double-layer Capacitors", Energy Conversion and Management, Vol. 51, pp. 2901-2912.
11. B. Vura, A. R. Boynuegri, I. Nakir, O. Erdinc, A. Balikci, M. Uzunoglu, H. Gorgun and S. Dusmez, 2010, "Fuel Cell and Ultra-Capacitor Hybridization: A Prototype Test Bench Based Analysis of Different Energy Management Strategies for Vehicular Applications", International Journal of Hydrogen Energy, Vol. 35, pp. 11161-11171.
12. B. Wu, M. A. Parkes, V. Yufit, L. D. Benedetti, S. Veismann, C. Wirsching, F. Vesper, R. F. Martinez-Botas, A. J. Marquis, G. J. Offer and N. P. Brandon, 2015, "Design and Testing of A 9.5 Kw Proton Exchange Membrane Fuel Cell-Supercapacitor Passive Hybrid", International Journal of Hydrogen Energy, Vol. 39, pp. 7885-7896.
13. M. Mansour, B. Faouzi, G. Jamel and E. Ismahen, 2014, "Design and Analysis of A High Frequency DC-DC Converters for Fuel Cell and Super-Capacitor Used in Electrical Vehicle", International Journal of Hydrogen Energy, Vol. 29, pp. 1580-1592.
14. M. Conte, 2010, "Supercapacitors Technical Requirements for New Applications", Fuel Cells from Fundamentals to Systems, Vol. 5, pp. 806-818.
15. Q. Li, W. Chen, Z. Liu, M. Li and L. Ma, 2015, "Development of Energy Management System Based on a Power Sharing Strategy for a Fuel Cell-Battery-Supercapacitor Hybrid Tramway", Journal of Power Sources, Vol. 79, pp. 267-280.
16. S. Lu, K. A. Corzine and M. Ferdowsi, 2007, "A New Battery / Ultracapacitor Energy Storage

System Design and Its Motor Drive Integration for Hybrid Electric Vehicles", IEEE Transactions on Vehicular Technology, Vol. 56, pp. 1516-1523.
17. M. J. Yang, H. L. Jhou, B. Y. Ma and K. K. Shyu, 2009, "A Cost-Effective Method of Electric Brake with Energy Regeneration for Electric Vehicles", IEEE Trans. on Industrial Electronics, Vol. 56, No. 6, pp. 2204-2212.
18. T. H. Kim, 2011, "Regenerative Braking Control of A Light Fuel Cell Hybrid Electric Vehicle", Electric Power and Components and Systems, Vol. 39, pp. 446-460.
19. Heliocentris, 2012, Nexa 1200 Power Module Instruction Manual.
20. J. S. Sim, 2008, "Development of the Sealed Type Ni-MH Secondary Battery for Hybrid System with Fuel Cell", Chonnam National University.
21. KIST, 2007, Development Trend of Supercapacitor.
22. B. H. Kim, O. J. Kwon, J. S. Song, S. H. Chen, B. S. Oh, 2014, "The Characteristics of Regenerative Energy for PEMFC Hybrid System with Additional Generator", International Journal of Hydrogen Energy, Vol. 39, pp. 10208-10215.
23. B. H. Kim, 2015, "The characteristics of regenerative energy for PEMFC hybrid system", doctoral thesis, Department of Mechanical Engineering, Chonnam National University.