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# Characteristics of Energy Harvesting in Flywheel Energy Storage System Based on Efficiency Map

**Jeonghyun Cho, Hongsik Hwang, Gwansoo Park, and Cheewoo Lee***

*Department of Electrical and Computer Engineering, Pusan National University, Busan 46241, Republic of Korea*

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**In this paper, the characteristics of energy discharge in a flywheel energy storage system (FESS) are analyzed according to load condition mapped in the efficiency of a generator. As time goes by, the electromotive force (EMF) of a generator decreases in an FESS as a power source, but output power is maintained by boosting the generator voltage in a bidirectional power converter (BPC). Using the principle of operation of a boost converter, the variation of voltage gain in a BPC is investigated under the condition of load change, and current is compensated for the reduction of back EMF in a generator as its speed goes down. The loss of the FESS is separated into that of its generator, bearings, and BPC through experimental evaluation, and it has been verified that the generator plays a significant role in the efficiency of the FESS.**

**Keywords :** flywheel, energy harvesting, efficiency map, energy storage system

## 1. Introduction

A flywheel energy storage system (FESS) having a bidirectional power converter (BPC) and a permanent magnet synchronous machine (PMSM) is able to store kinetic rotational energy and discharge the stored energy whenever required. An FESS has the advantages of high efficiency, large energy density, numerous cycles of charge and discharge, and environment-friendly characteristics in comparison with other energy storage units. Its applications vary from uninterruptible power supplies (UPS) to micro grids along with wind power plants, vehicle regenerative braking and so on. In the past decade, for the improvement of an FESS, a lot of researches have been done on the issues of bearing, motor/generator design, power system, and control algorithm [1, 2]. Among the various element technologies, the discharge control of a flywheel rotor from kinetic energy to electric energy is the core part of the FESS.

In discharging energy from an FESS, the magnitude of electromotive force (EMF) induced in a PMSM decreases with respect to time, and hence, to supply constant output, the current of the PMSM must be increased by modulating voltage gain in a BPC. Since the PMSM as a generator is operated in the wide range of speed and torque, it is necessary to study the influence efficiency in the generator on an FESS in case of discharge mode. However, most of papers on a flywheel generator deal with either torque control in charge mode [3] or stable voltage control in discharge mode. In [4], a discharge strategy in an FESS for wide speed operation is discussed, and its main purpose is to obtain a robust discharge system using a flywheel. The variation of voltage and energy efficiency in an FESS by load resistance has been analyzed in [5], and experimental results are also given. However, the reason for efficiency change with respect to load resistance is not explained.

The characteristics of energy harvesting in an FESS based on the efficiency map of a generator is analyzed in this paper. Using the principle of operation of a boost converter, the variation of voltage gain in a BPC is investigated under the condition of load change, and current is compensated for the reduction of back EMF in a generator as its speed goes down. In this paper, the efficiency of a PMSM is mapped in the region of torque versus speed to check the contour of current on the efficiency map. For experimental verification, an FESS consisting of a PMSM, a flywheel, and a BPC has been fabricated, and all the three parts of the flywheel system are characterized to determine their losses at three different load points. In addition, the efficiency of the FESS is


*Corresponding author: Tel: +82-51-510-7377
Fax: +82-51-513-0212, e-mail: cwlee1014@pusan.ac.kr

compared under the condition of load change by including losses in a generator, bearings, and a BPC from the experimental and analytical perspective.

## 2. Flywheel Energy Storage System

An FESS is composed of a flywheel, a PMSM as either a motor or a generator, a BPC, rolling bearings, and a load resistor as shown in Fig. 1. This system stores the energy in the flywheel when the input power is stable and uses the stored energy when needed to provide power to the desired location.

### 2.1. Energy Storage Capacity of a Flywheel

In an FESS, there is a flywheel having a mechanical coupling with a PMSM which accelerates the flywheel to make kinetic energy from electric power in case of energy charge. The total amount of kinetic energy is obtained as

$$K_e = \frac{1}{2} \cdot I \cdot \omega^2 \quad (1)$$

where $I$ and $w$ are the moment of inertia and the angular velocity of a flywheel, respectively.

### 2.2. Energy Harvesting in an FESS

The rotational kinetic energy of a flywheel is converted to electric energy through a PMSM as a generator along with a bidirectional power converter, and output voltage is modulated by the converter. Fig. 2 shows the discharge characteristics of an FESS, and the mechanism of variation in speed with respect to time is explained. Due to generator voltage proportional to the speed of a flywheel, the induced voltage is reduced as time goes by. Since the voltage of 350 Vdc in dc link is always bigger than the back EMF of 106 Vrms, as given in Table 1, at the rated speed of 3,000 rpm, a bidirectional converter is operated as a boost converter to supply constant DC voltage to an output stage, and the minimum of flywheel speed is determined by voltage gain in the converter under the condition of maintaining DC output voltage. The voltage gain of a boost converter is given in equation (2), and the gain is determined by the ratio of phase resistance to load resistance [6]. Under the assumption that constant voltage is guaranteed by a BPC, as a result, the total amount of energy extracted from an FESS is determined by the maximum and minimum speed as shown in equation (3).

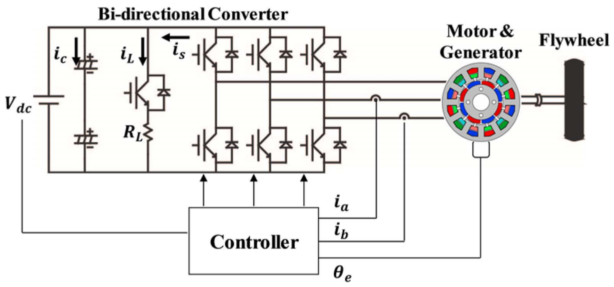


**Fig. 1.** (Color online) Flywheel energy storage system.

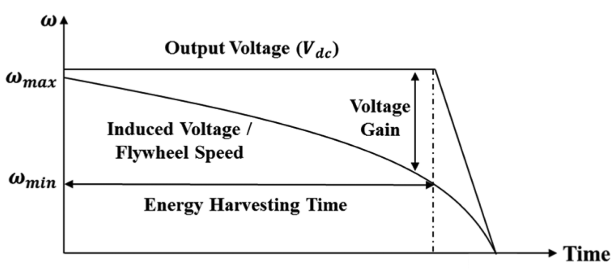


**Fig. 2.** Energy discharge of an FESS with respect to time.

**Table 1.** Parameters of PMSM and flywheel.

| Parameter | Value |
|---|---|
| phase | 3 |
| stator / rotor poles | 12 slot / 8 poles |
| no. of turns per pole, turns | 26 |
| phase resistance, ohm | 1.1 |
| stator inductance, mH | 2.563 |
| rated phase current, Arms | 6.7 |
| rated rotor speed, r/min | 3,000 |
| rated torque, N·m | 6.53 |
| back EMF, mVrms/rpm | 35.19 |
| material of wheel | 6061-T4 |
| wheel weight, Kg | 26.2 |
| wheel OD, mm | 320 |
| wheel height, mm | 120 |
| moment of inertia, Kgm$^2$ | 0.332 |

$$V_G = \frac{V_{out}}{V_{in}} = \frac{1}{(1-D)} \times \frac{1}{(1+R_s/R_L/(1-D)^2)} \quad (2)$$

$$K_e = \frac{1}{2} I(\omega_{max}^2 - \omega_{min}^2) \quad (3)$$

where $V_G$, $R_s$, $R_L$, and $D$ are the voltage gain, phase resistance, load resistance, and duty ratio, respectively. Also, $\omega_{max}^2$ and $\omega_{min}^2$ are maximum and minimum angular velocity in a flywheel, respectively.

In an FESS, kinetic energy in a flywheel becomes a power source to a three-phase converter through a generator. Since input voltage is equal to output voltage in case of zero duty ratio, a capacitor is charged with a value of $\sqrt{6}e_a$ of voltage as given in (4). Therefore, input voltage $V_{in}$ in (2) is expressed as (4), and phase resistance ($R_s$) is expressed as equation (5) because there is a three-phase wye connection of resistance ($R_a$) in the generator.

$$V_{in} = \sqrt{2} \cdot \sqrt{3} \cdot e_a \quad (4)$$

$$R_s = 1.5 \cdot R_a \quad (5)$$

where $e_a$ and $R_a$ are the back EMF and resistance of each phase in a generator, respectively

## 3. Performance of an FESS by Load Change

Table 1 shows the parameters of the FESS built in this paper, and the rated speed, torque, and moment of inertia are 3,000 rpm, 6.53 Nm, and 0.332 Kgm$^2$, respectively. To numerically evaluate the discharge feature of the FESS depending on load, key variables such as voltage gain in the converter, current in the generator, and its efficiency are carefully examined by varying load in the selection of 250.0 ohm, 125.0 ohm, and 83.3 ohm.

Figure 3 illustrates the voltage gain of the BPC as a function of duty ratio under three resistance conditions in load. By referring to (2), as load resistance goes up, the smaller ratio of phase resistance to load resistance leads to the increase of voltage gain as shown in Fig. 3.

BPC output current with respect to duty ratio can be obtained as shown in (7) by substituting the capacitor charge balance equation of (6) into (2), and assuming that $V_{in}$ is the peak value of the generator line-to-line back EMF, this current can be regarded as the generator q-axis current, in the d-q vector control method.

$$\langle i_c \rangle = 0 = (1-D)I_s - \frac{V_{out}}{R_L} \quad (6)$$

$$I_s = \frac{V_{in}}{(1-D)^2 R_L} \times \frac{1}{(1 + R_s/R_L/(1-D)^2)}$$
$$= \frac{V_{out}}{(1-D)^2 R_L V_G} \times \frac{1}{(1 + R_s/R_L/(1-D)^2)} \quad (7)$$

In order to predict the characteristics of the generator, the current waveforms in accordance with the speed is

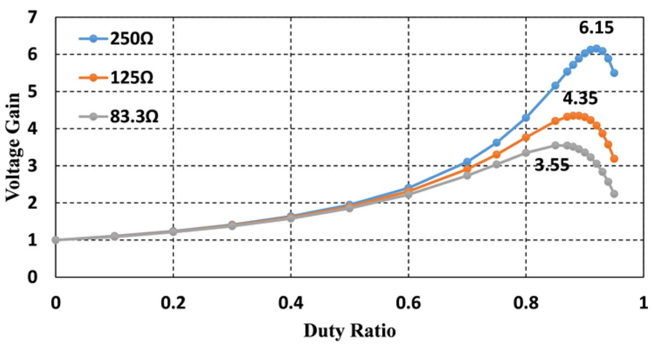


**Fig. 3.** (Color online) Voltage gain as a function of duty ratio at three resistance loads.

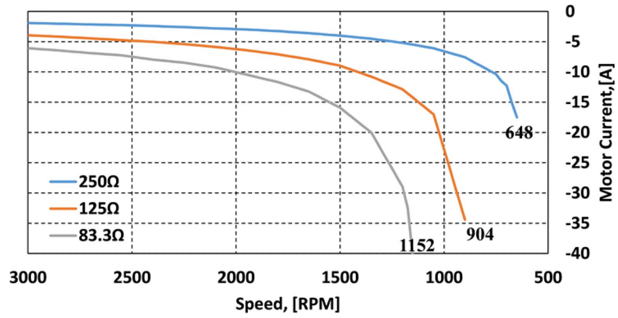


**Fig. 4.** (Color online) Current locus of the PMSM at three different load conditions.

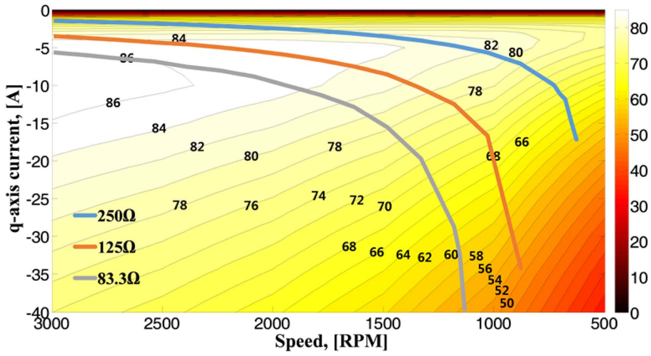


**Fig. 5.** (Color online) Generator efficiency map and contour current at three load conditions.

required and it can be obtained by substituting the duty ratio and voltage gain that produce the desired output voltage corresponding to the back EMF varying with speed into (7). The duty ratio and voltage gain with respect to speed are calculated by substituting equation (4) into (2). Fig. 4 denotes the trajectory of the generator current as a function of speed satisfying the output stage 350 volts under three load conditions, and shows the minimum speed of the generator. As flywheel speed goes down, the smaller back EMF leads to the increase of current to produce the constant output, and depending on the load resistance, the magnitude of the current varies at the same speed due to the difference in voltage gain.

To investigate the relationship between variations of generator operating point depending on load and FESS efficiency, the efficiency of a PMSM is mapped in the region of torque versus speed, and contour of generator current is shown on the efficiency map as shown in Fig. 5. When the load resistance is 250.0 ohm, generator operating points moves from the low efficiency to the high efficiency. On the other hand, the 125.0 ohm and 83.3 ohm shifts from the high efficiency to the low efficiency. Therefore, the system efficiency is expected to be different depending on the load resistance.

## 4. Experimental Results and Discussion

### 4.1. Experimental Results

Figure 6 shows the experimental setup and Fig. 7 depicts the control block diagram of the flywheel energy discharge mode. The PMSM works as a motor to accelerate the flywheel up to 3,000 rpm, and then the synchronous machine is switched over to a generator in order to make output stage 350 volts. The voltage and current are controlled using a proportional-integral controllers, and the output voltage is constantly controlled by modulating q-axis current at d-axis current zero conditions. Experiments is performed by varying load in the selection of 250.0 ohm, 125.0 ohm, and 83.3 ohm to analyze the discharge feature of the FESS in the range of 500 to 1500 watt. Fig. 8 demonstrate the experimental results and shows the motor rotation speed, output voltage, generator q-axis current, and load current under each load condition. As load resistance goes down, the smaller voltage gain lead to decreases of the generator speed range and supply time that guarantee the output voltage of 350 volts. Table 2 summarizes the experimental results and Fig. 9 shows the amount of energy and efficiency at each load condition. The kinetic energy is calculated by substituting the minimum speed in Table 2 into the (2), and the generated energy is calculated by multiplying the voltage, current and time in Table 2. It is found that the amount of generated energy is the largest at 250.0 ohm, but the efficiency is the highest

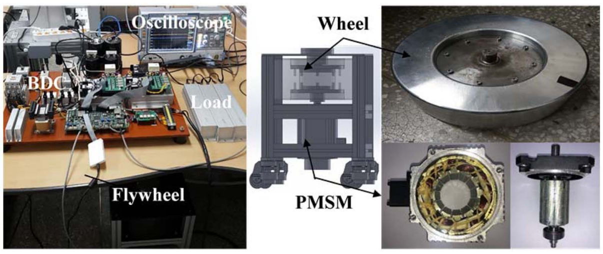


**Fig. 6.** (Color online) Experimental setup.

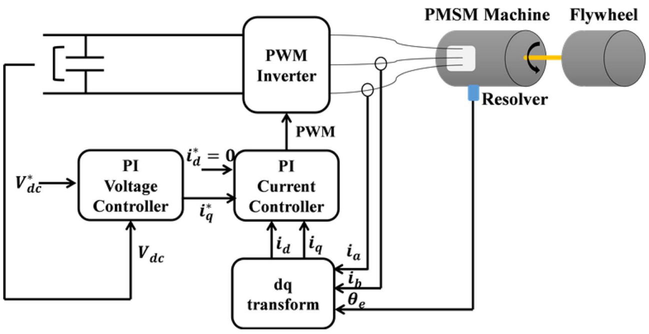


**Fig. 7.** (Color online) Control block diagram of the Flywheel energy discharging mode.

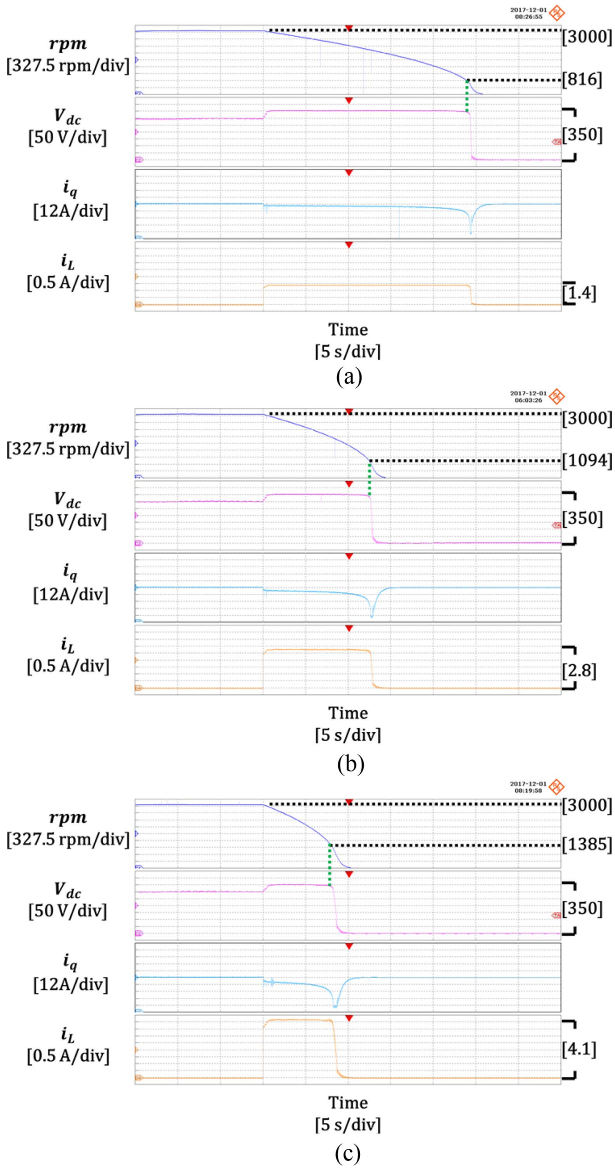


**Fig. 8.** (Color online) Experimental results of flywheel at three different load conditions. (a) 250.0 ohm, (b) 125.0 ohm, (c) 83.3 ohm.

**Table 2.** Energy extraction characteristic at various load.

| $R_L$ [ohm] | output [W] | $rpm_{min}$ | $V_{rms}$ | $I_{rms}$ | time [sec] | $V_G$ |
|---|---|---|---|---|---|---|
| 250.0 | 490 | 816 | 350 | 1.38 | 23.3 | 5.0 |
| 125.0 | 980 | 1,094 | 350 | 2.74 | 11.2 | 3.7 |
| 83.3 | 1,470 | 1,385 | 347 | 4.08 | 7.2 | 2.9 |

at 83.3 ohm. Therefore, to clarify the reason for characteristics change with respect to load resistance, the efficiency of the FESS is compared under the condition of load change by including losses in a generator, bearings, and a BPC.

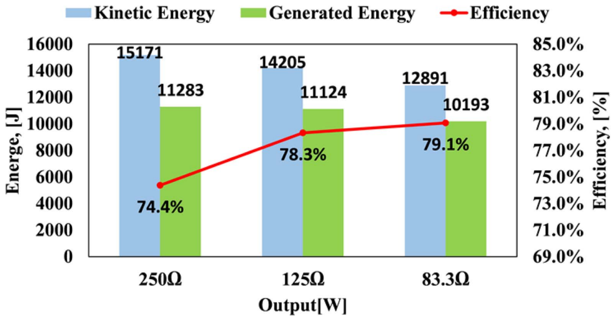


**Fig. 9.** (Color online) Energy efficiency of flywheel at three different load conditions.

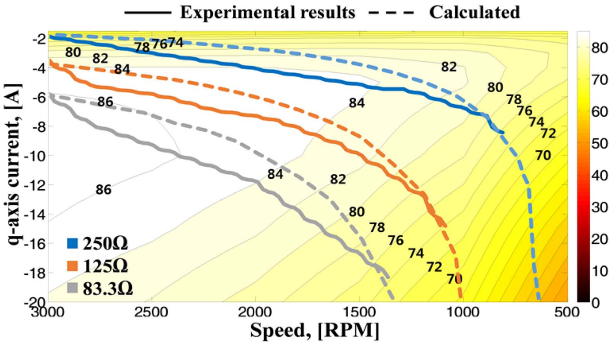


**Fig. 10.** (Color online) Paths of q-axis current on the efficiency map of a generator with respect to load resistance in case of energy discharged from a flywheel.

### 4.2. Analysis of FESS Loss Characteristics

Figure 10 shows the trajectory of current on the efficiency map of a generator at three load resistances. Dashed and solid lines represent the contour of calculated current in (6) and that of actual current in experiments, respectively. By adding current charged to a capacitor ($i_c$) in Fig. 1, the absolute value of the measurement of q-axis current ($i_s$) is relatively larger than the calculation of current during most of speed. In other words, the calculated current is determined under the condition of zero capacitor

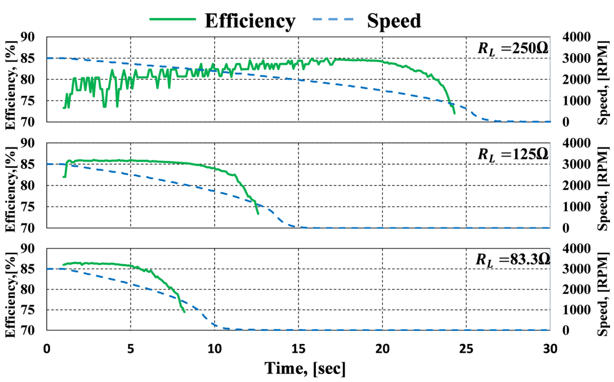


**Fig. 11.** (Color online) Efficiency and speed in the generator with respect to time.

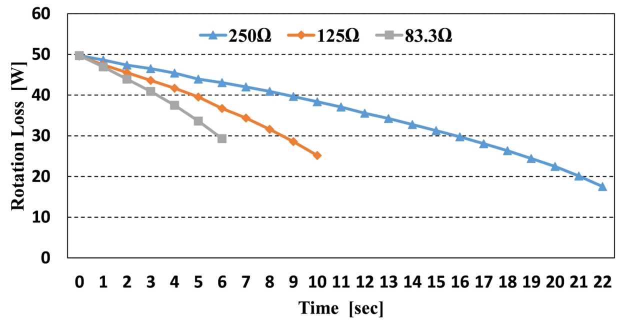


**Fig. 12.** (Color online) Flywheel rotation loss at the three different loads.

current as given in (6).

For the purpose of analyzing the efficiency of the generator in the mode of discharge, its efficiency and speed with respect to time are measured as shown in Fig. 11. In case of 250.0 ohm, the duration of energy supplied from the flywheel is longest, but generator efficiency is worst during most of time compared to other two load resistors. On the other hand, there is the shortest period of time in the load of 83.3 ohm, but its efficiency is the best. Consequently, the average efficiency of the generator at 250.0 ohm, 125.0 ohm, and 83.3 ohm are 81.7%, 84.6%, and 84.9%, respectively.

In order to evaluate the rotation loss of the flywheel, the reduction of rotational speed with respect to time is measured under the condition of no load. The rotation loss is determined by equation (8), and Fig. 12 illustrates the calculation of rotation loss with respect to load resistance.

$$P_{rotation\ loss} = \frac{dK_e}{dt} = \frac{1}{2} \cdot I \cdot (\omega_t^2 - \omega_{t+1}^2) \tag{8}$$

**Table 3.** Energy loss characteristics of FESS at three loads.

| | | | 250.0 Ω | 125.0 Ω | 83.3 Ω |
|---|---|---|---|---|---|
| kinetic energy | | J | 15,171 | 14,205 | 12,891 |
| | | % | 100 | 100 | 100 |
| generator loss | copper loss | J | 805 | 1,333 | 1,383 |
| | | % | 5.31 | 9.38 | 10.73 |
| | core loss | J | 1,971 | 897 | 630 |
| | | % | 12.99 | 6.32 | 4.89 |
| rotation loss | | J | 823 | 437 | 287 |
| | | % | 5.47 | 3.07 | 2.22 |
| converter loss | | J | 282 | 414 | 397 |
| | | % | 1.86 | 2.91 | 3.08 |
| generated energy | | J | 11,283 | 11,124 | 10,193 |
| | | % | 74.37 | 78.31 | 79.07 |

Table 3 summarizes the characteristics of energy loss in the FESS at three loads. In this system, there is mechanical rotation loss in rolling bearings, and the loss deteriorates during longer period of time. If there is no bearing loss, FESS efficiency is directly proportional to generator efficiency, and the generator has core and copper losses. Core and copper losses are worst in the load of 250.0 ohm and 83.3.0 ohm, respectively. In other words, it is seen that core and copper losses vary in the generator based on its operating region, and hence, generator efficiency is correspondingly changed. The BPC loss is only calculated by subtracting both generator and rotation losses from total loss, and the converter efficiency approximately ranging from 96% to 97% is reasonable.

## 5. Conclusion

In this paper, the characteristics of energy discharge in an FESS are analyzed according to load condition mapped in the efficiency of a generator. As time goes by, the electromotive force of a generator decreases in an FESS as a power source, but output power is maintained by boosting the generator voltage in a bidirectional power converter. Using the principle of operation of a boost converter, the variation of voltage gain in a BPC is investigated under the condition of load change, and current is compensated for the reduction of back EMF in a generator as its speed goes down. The loss of the FESS is separated into that of its generator, bearings, and BPC through experimental evaluation, and it has been verified that the generator plays a significant role in the efficiency of the FESS. Since core and copper losses are changed in the FESS due to its wide region of speed and torque, it is not simple to improve the performance of the FESS. Therefore, analytical consideration for variable speed has be included into the implementation of an FESS by mapping current paths on the efficiency of the generator at different loads. Also, the effective utilization of energy has been verified in terms of selecting a proper load in the FESS.

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