Optimized Design for AMB Based Flywheel Energy Storage and Power Conversion Systems

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Abstract: A flywheel energy storage system (FESS) works by accelerating a flywheel to a very high speed and maintaining the energy in the system as rotational energy. An Active magnetic bearing flywheel (AMB-FW) has many advantages such as low friction loss, short time distance, and no chemical waste. They can be expected to replace lead acid batteries as an energy resource. Our research group aimed to construct a new static FESS by using AMB-FW. The charge and discharge unit (CDU) that controls the charge and discharge energy dominates the static system. This paper reports on the result of creating and controlling CDU through simulations and experiments.

Keywords: Flywheel Energy Storage System(FESS), Active Magnetic Bearing-Flywheel (AMB-FW), Charge and Discharge Unit (CDU), Optimized Design, Power Conversion System

Introduction

There have been several technical papers on flywheel energy storage systems (FESS) [1,2,3,4,5]. We mounted an active magnetic bearing flywheel (AMB-FW) on an electric vehicle and investigated ways for effective energy use. The most important requirement is the optimization of the energy conversion efficiency. However, there have been few papers on FESS energy efficiency. We aimed to construct a new static FESS by using AMB-FW to validate its energy efficiency. The system’s key component is a charge and discharge unit (CDU), which converts rotational energy to electric energy. We refrained from using a commercially made CDU because its controls and specifications would have been fixed as designed by the manufacturer Thus we determined to create our own CDU to be able to optimize the controls and specifications. We developed an original CDU and a CDU simulation model and compared the simulation and experimental results. This paper reports on those results.

Fig.1 Overview of AMB-FW

Table.1 Specification of induction motor

Item	Value
Structure Type	Squirrel Cage
Nominal Power	600 [W]
Voltage	AC 100 [V]
Frequency	450 [Hz]
Inertia	0.186 [kgm2]
Stator Resistance	0.3 [Ω]
Stator Inductance	0.2 [mH]
Pole	2

Active magnetic bearings flywheel (AMB-FW)

Figure 1 shows an overview of the AMB-FW. The flywheel has 8-homo-poles and a rotation speed of 27000 RPM (450Hz). The moment of inertia is 0.186 kg m^2. The flywheel can store about 200 Wh at the maximum rotational speed. Table.1 shows the specifications for the motor rotating the flywheel. The motor is a three-phase squirrel-cage induction motor. The nominal voltage is AC 100 V and the nominal output is 600 W.

Charge and discharge unit (CDU)

Figure 2 shows an overview of the CDU. Table 2 shows its specifications of CDU. The input voltage is AC 100 V. The CDU is constructed from two circuits: a rectification circuit and a three-phase full bridge inverter circuit. The rectification circuit rectifies the input of AC 100 V to about DC 142 V. The voltage is maintained by a capacitor. The inverter circuit converts the capacitor's DC voltage to AC voltage and supplies the energy to the flywheel. The CDU is controlled by adjusting the frequency and voltage target value.

Fig.2 Overview of CDU

Table.2 Specifications of CDU

Item	Value
Length	430 [mm]
Width	330 [mm]
Height	135 [mm]
Circuit method of Unit	Full Bridge inverter
Input Capacitance	1 [kW]
Input Voltage	AC 100 [V]
Output Voltage	AC 100 [V rms]
Switching Frequency	20 [kHz]

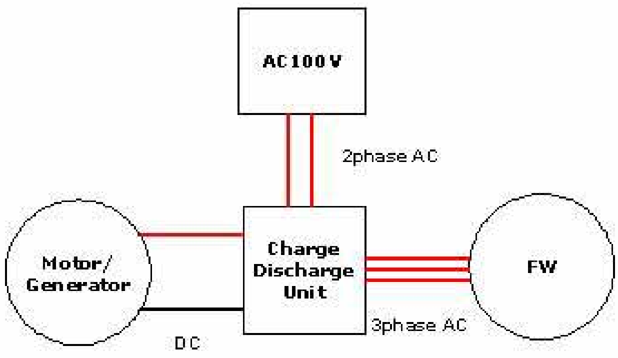

Fig.3 Static energy system

Static energy system

Figure 3 shows the static energy system using AMB-FW. The system is comprises a flywheel, CDU, AC 100 V resource, and motor/generator. The system functions are as follows. First, charge the flywheel by using the energy from the energy resource. Second, discharge the flywheel and supply regenerated energy to the motor. Third, when the motor brakes, use the motor as a generator and supply a regenerated energy to the flywheel. All functions are controlled by the CDU. Our final goal was to optimize the system energy flow and improve the efficiency.

Main circuit of CDU

Figure 4 shows the main circuit of the CDU. The rectification circuit is on the left. This circuit rectifies the input AC 100 V to DC 142 V. The capacitor holding the DC voltage exists in the middle, and has a capacitance of 6000 μF. The circuit on the right is three-phase full bridge inverter circuit that consists of six insulated gate bridge transistor (IGBT) switches. The switches are controlled by the switching generator. The switching generator creates pulse width modulation (PWM) pulses from target values, such as the frequency and voltage. PWM pulses are created by comparing the desired sine signal with carrier pulses. One of the important things for improving energy conversion efficiency is the carrier frequency. If the carrier frequency is high, the number of switching increases. This increases switching loss and lowers efficiency. However, if the switching frequency is too low, the desired sine wave is unavailable. Thus, we needed to configure an adequate carrier frequency. In experiments, the target value was given only the frequency value by using feed forward control. The voltage value was uniquely given from the frequency value by using V/F constant control. We created a simulation model based on the main circuit of CDU.

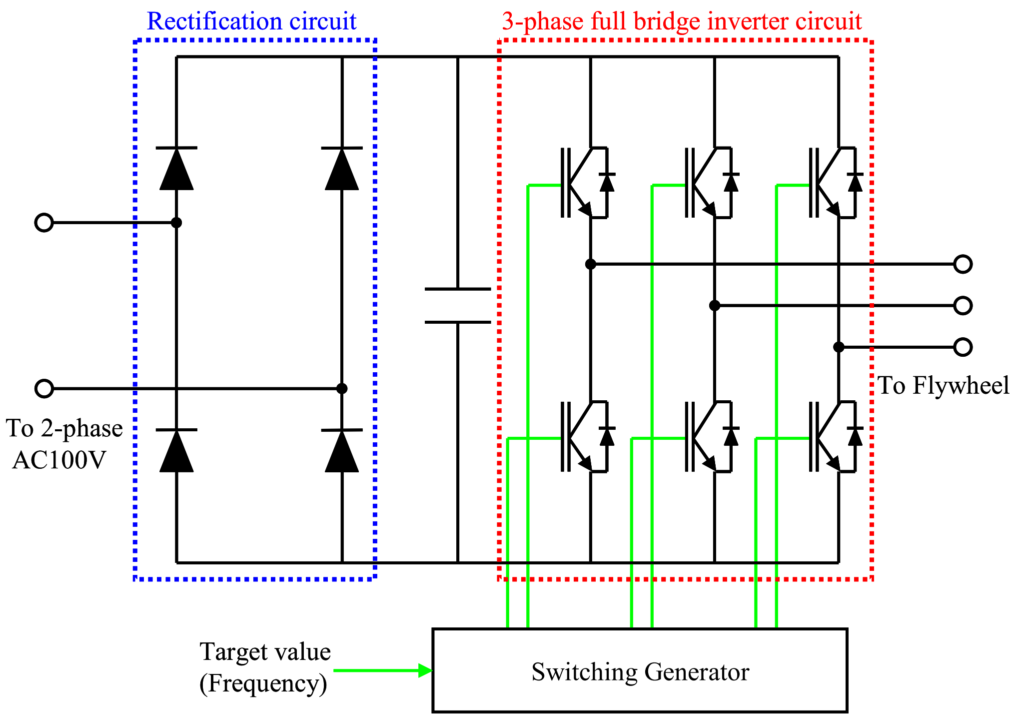

Fig.4 Main circuit of CDU

Comparison simulations with experiments

We charged the flywheel by using the original CDU. Figures 6-8 show comparisons between the simulations and experiments. Fig.6 shows flywheel rotation speed; Fig.7, the input current; and Fig.8 the input voltage at an input capacitor. Fig.6 shows that the simulation and experiment result had good agreement for the rotation speed, which began at about 4200 rpm and finished at about 4320 rpm.

As shown in Fig.7, the experimental data were full of noise with a central focus at about 0 A. However, the simulation data had a constant vibration with an amplitude of about 16 A. The difference was inferred to depend on a difference in sampling frequency. The simulation sampling frequency was 20 kHz. In contrast, the experiment sampling frequency was 200 Hz. Therefore, the mismatch between the experimental and simulation data was because of the missing experimental data. The average for the experimental data is 0.65 A, while that for the simulation data is 0.48A. The two average values are roughly matched.

Voltage data showed clear differences in the simulation and experiment results, as shown in Fig.8. The former showed constant data at about 140 V, while the latter, presented noisy data with a focus at about 110 V. This is because of the losing power balance between the input and output. In the simulation, the power resource was unlimited. However, in the experiment, the power resource was limited. Thus, this difference suggests that there was voltage depression caused by the limited power resource.

The input energy at the inverter is calculated as follows:

$$E_{ix} = \int I_{in} \cdot V_{in} dt \tag{1}$$

where I_{in} is the input current [A] and V_{in} is the input voltage [V] at the capacitor. The output energy to the flywheel is calculated as follows:

$$E_{FW} = I\omega^2 \tag{2}$$

where I is the flywheel inertia [kg m^2], and ω is the flywheel rotation speed [Hz].The charging efficiency is calculated as follows:

$$\eta = \frac{E_{FW}}{E_{in}}. \tag{3}$$

Using Eqs.1 and 2, the input and output energies were found to be0.3823 and 0.3035 Wh, respectively, in the simulation. Therefore, the simulation efficiency was 79.4%. Similarly, experiment input and output energies ware found to be 0.4021 and 0.2936 Wh, respectively. Therefore, the experiment efficiency was 73.0%. There was an error of 6%, which may depend on thermal loss, caused by high-speed switching in the experiment. However, the simulation did not consider the thermal loss.

Conclusion

In this study, we developed a CDU simulation model and validated the adequacy of the model by comparison with experimental results. However, we did not perform flywheel discharging experiments. Thus, we will perform such experiments and compare the results with the simulation and experimental results derived in this study. In the future, we will consider the CDU controls and specifications to optimize the FESS system by using AMB-FW and improve the system efficiency. One of the important methods for doing this would be to optimize the carrier frequency to improve the energy conversion efficiency. We intended to propose a criterion for carrier frequency by using frequency analysis and validate the availability of the criterion.

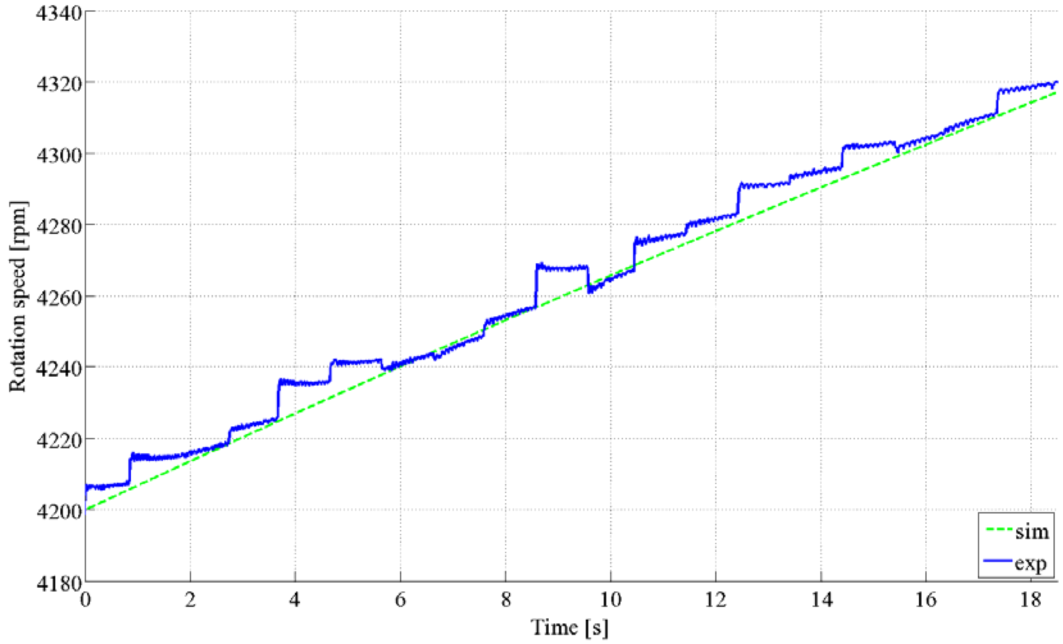

Fig.6 Comparison simulations and experiments (flywheel rotation speed)

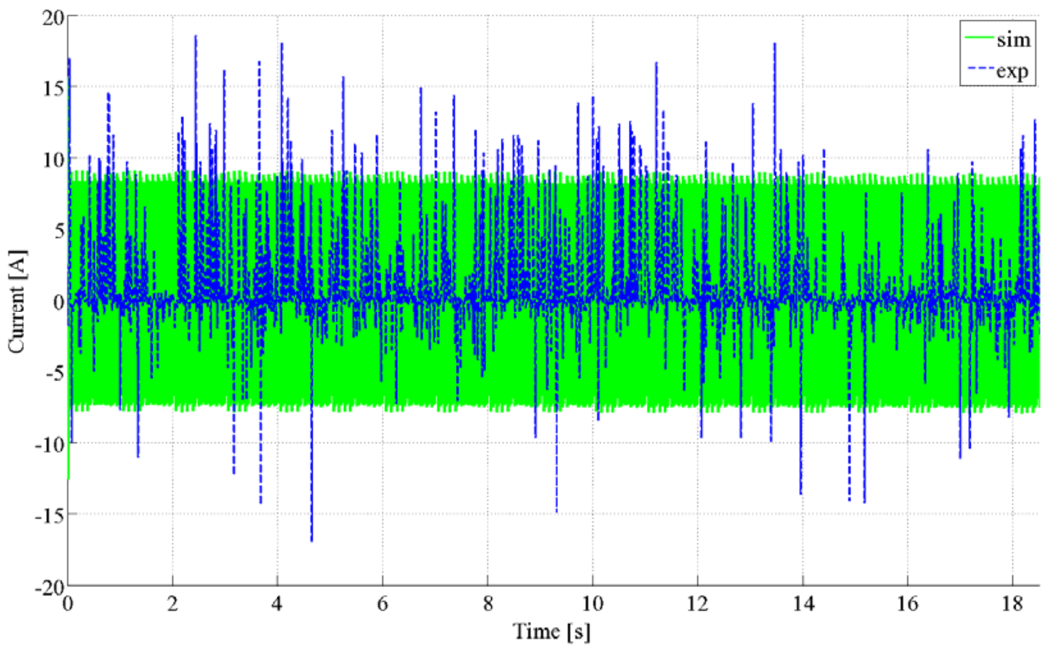

Fig.7 Comparison simulations and experiments (input current)

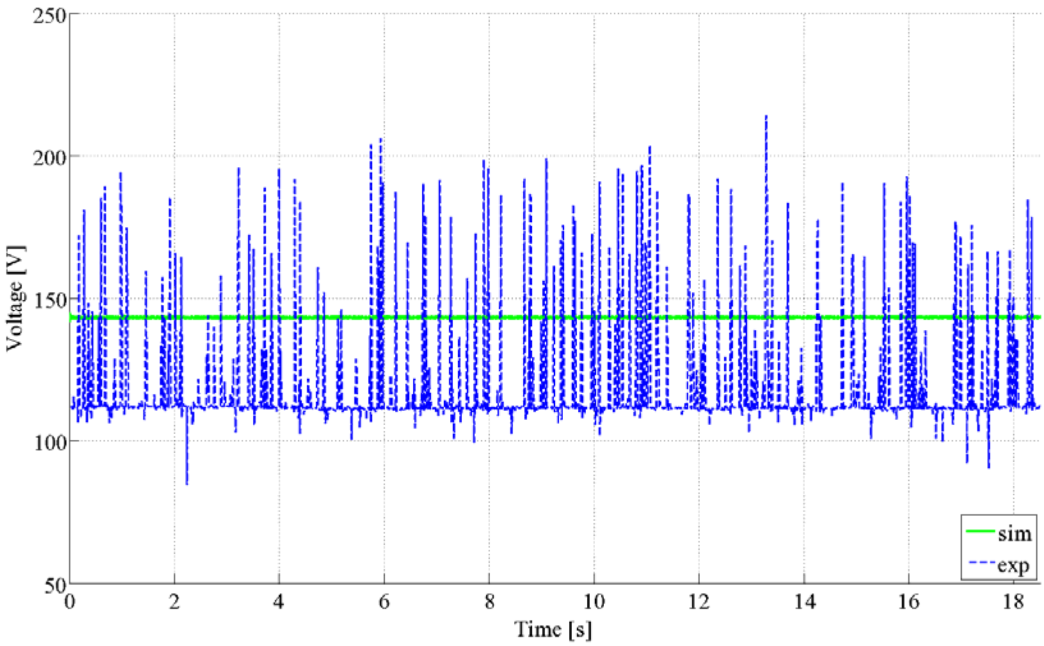

Fig.8 Comparison simulations and experiments (input voltage)

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