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Improvement of Compact Energy Storage Flywheel System using SMB and PMB

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Abstract: Since few years ago, electrical energy storage had been attracted as an effective use of electricity and coping with the momentary voltage drop. Above all, energy storage flywheel systems using superconductor have advantages of long life, high energy density, and high efficiency. Our experimental machine uses a superconducting magnetic bearing (SMB) together with a permanent magnet bearing (PMB) and plans to reduce the overall cost and cooling cost. Energy storage flywheel systems operate by storing energy mechanically in a rotating flywheel. The generating motor is used to rotate flywheel and to generating electricity from flywheel rotational. The generating motor consists of 2-phase 4-poles brush-less DC motor and a Hall sensor.

A purpose of this research is the development of a compact energy storage flywheel system using SMB and PMB. This paper shows the new model of flywheel by using yajirobei (balancing toy) principle that has higher storage energy comparing with conventional one, the improvement and evaluation of motor drive (DC motor) to increase the speed rotating, and estimating the system at momentary voltage drop.

Keywords: Flywheel, Superconducting Magnetic Bearing, Energy Storage

1. Introduction

Many serious damages may result if momentary voltage drop or blackout suddenly happened, especially in data centers, hospitals, railroads, and communication systems. Electrical energy storage becomes famous as an effective use of electricity and coping with the momentary voltage drop. Above all, flywheels for electrical storages using superconductor have advantages of long life, high energy density, high efficiency, pollution and toxic material disposal problems.

Energy storage flywheel systems operate by storing energy mechanically in a rotating flywheel. Electrical energy is stored by using a motor which spins the flywheel, thus converting the electric energy into mechanical energy. The energy that can be stored is depending on its rotational velocity and moment of inertia. The energy can be more stored if flywheel rotates with high rotational speed. The problems at commonly flywheel system are big vibration occurred at rotor when rotating, so it’s difficult to increasing the speed rotating.

Here, a new energy storage flywheel system is proposed using a Superconducting Magnetic Bearing (SMB) and a Permanent Magnetic Bearing (PMB) to support a rotor. We proposed this system whose concept is different from others. The SMB mainly suppresses the vibrations of the rotor and the PMB passively controls the position of the rotor. Furthermore, we suggest a new model of flywheel by using yajirobei (balancing toy) principle to have higher storage energy comparing with conventional ones and good stability for rotating at high speed. Figure 1 shows the model of yajirobei principle. As shown in Figure 1, the center of gravity of mass is lower than support point, so the mass have more stability. By using this principle, the flywheel is made such that the center of gravity to be lower than the center of support point, moreover the flywheel will have more moment of inertia at rotating. We also purpose to improve and evaluate of motor drive (DC motor) to increase the speed rotating, evaluate charge-discharge system for momentary voltage drop [1, 2, 3].

2. Design of Flywheel System

The design of a compact energy storage flywheel system is shown in Figure 2. As shown in Figure 2, the energy storage flywheel system consists of a PMB, a generating motor, a flywheel, and a SMB. Structure of flywheel is made such that the center of gravity to be lower than the center

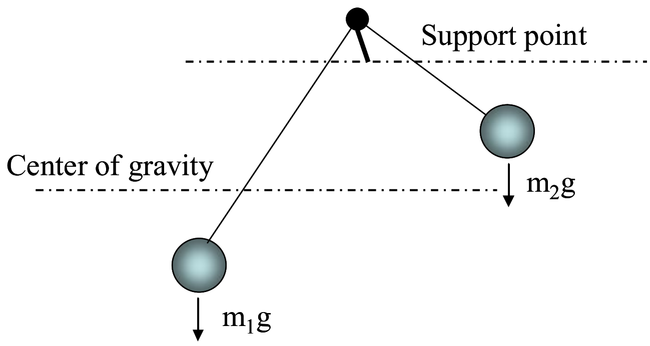


Fig.1 Model of Yajirobei principle

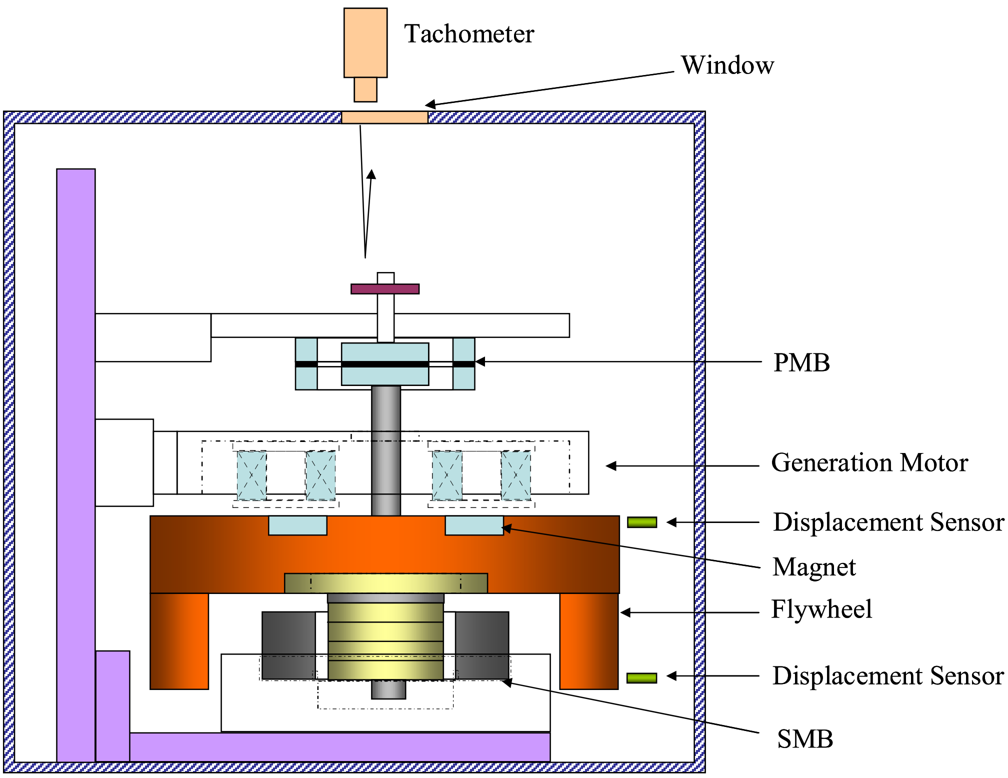


Fig.2 New energy storage flywheel system using PMB and SMB

of support point. Therefore, the flywheel will be more stable both in rotating condition or not. Beside this, the flywheel will have more inertia moment at rotating, because weight of flywheel mostly located on the outside. In addition, Table 1 shows basic specifications of the flywheel system. The flywheel rotor is supported by two non-contact bearings, a PMB in the upper part and a SMB in the lower part. By using SMB both axial and radial type, rotor is actually supported by one support point. The cooling of SMB just in the lower part is more effective by using the PMB in the upper part instead of SMB [1, 2, 3].

The generating motor drives the flywheel and consists of a brushless DC motor with 2-phase 4-poles to generate electric power. To minimize the length of flywheel rotor, 4 coils are set horizontally. And to make the attraction force of motor more effective on flywheel rotation, the magnet installed in the upper part of the flywheel is used as a rotor of the DC motor. Rotor vibrations were measured by using displacement sensors at the top and the bottom of flywheel. These are installed in a vacuum chamber, and a vacuum pump is used to keep high vacuum for the reduction of windage loss. In addition, a cryocooler is used for cooling the superconductor.

Flywheel storage energy is stored in the rotor in proportion to its rotational inertia, and corresponding to the square of the angular velocity. The flywheel storage energy E [J] is shown in equation (1)

$$E = \frac{1}{2} I\omega^2 = \frac{1}{4} m(r\omega)^2 \qquad (1)$$

Where I [kg m2] is the moment of inertia about axis of rotation, m [kg] is a rotating mass, r [m] is a radius of rotation, and ω [rad/s] is a rotational speed.

Table 1 Basic specifications of system

Items	Basic Specifications
Rated rational speed range	4000－5000 rpm
Weight of rotational body	0.24 kg
Full length of rotational body	0.094 m
Energy input-output device	Generating Motor
Number of the coils	650turnx 4poles
Diameter of the coil wire	0.3 x 10^{-3} m
Gap of SMB	0.5 x 10^{-3} m （normal conditions）

3. Magnetic Bearing

3.1 Structure of SMB

Radial and axial type of SMB was suggested to more suppress vibrations and supports the weight of the rotor. The SMB consists of a circle-shaped high-temperature superconductor $D_{Y1}Ba_2Cu_3Ox$ (OD; 45.0mm, ID; 26mm, Width: 16mm) and four circle-shaped Neodymium magnets (OD; 25mm, Width; 3mm). The magnetic poles of the Neodymium magnets are arranged with alternate polarities, such as NS-SN-NS-SN. Thus, the magnetic flux is produced so that the levitation force becomes large [1, 2].

Figure 3 shows the structure of the SMB. To support the weight of flywheel stronger, the SMB use both radial type and axial type as shown in Figure 3. The SMB has other merit easily to suppress the vibration (a prevention of axial vibration).

3.2 Structure of PMB

The PMB using repulsion force between permanent magnets has advantages more than the conventional active magnetic bearings. The advantages using PMB are no friction/abrasion in the bearing part, maintenance-free, no necessary for control device, and usage under the special environmental. The total system can be miniaturized because the PMB does not need control unit. However, the stiffness can get only small and constant values in comparison with the active control magnetic bearing. In general, PMBs using repulsion forces are very unstable in the axial direction.

The structure of the PMB is shown in Figure 4. As shown in Figure 4, PMB consists of two magnets for the stator (Φ37×Φ28×4.5mm, surface magnetic flux density 0.42T), two magnets for the rotor (Φ18×Φ6×3.8mm, surface magnetic flux density 0.46T) and one spacer for each rotor and stator (stainless steel, dimensions Φ12×Φ6×1mm and Φ36×Φ28×1mm). The spacers adjust the repulsion force in the axial direction without influence on the repulsion force in the radial direction [1, 2, 3, 4].

Figure 5 shows repulsion force characteristics of PMB in the axial (solid lines) and the radial direction (dotted lines). Here, repulsion force in radial direction is more defensible to minimize vibrations. Rotor has vibration in the range maximal ±0.5mm to radial direction when rotating. As shown in Figure 5, the repulsion forces in the radial direction are ±4N.

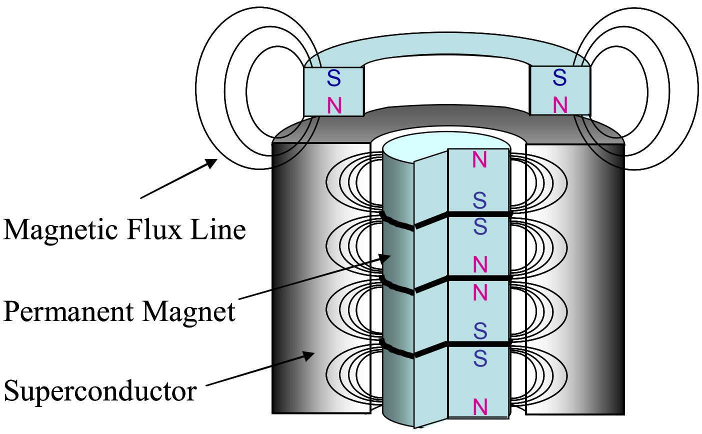


Fig.3 Structure of SMB

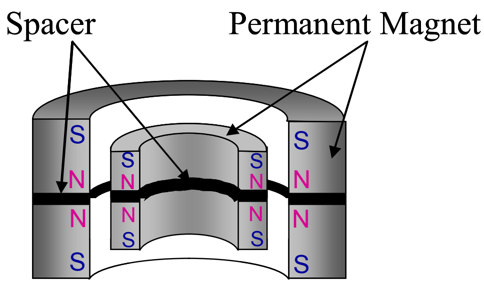


Fig.4 Structure of PMB

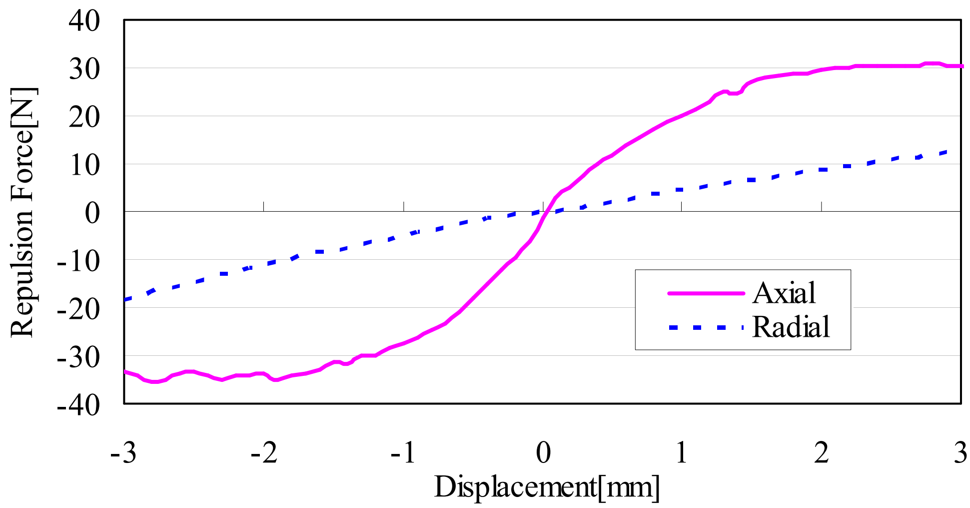


Fig.5 Repulsion force characteristic of PMB

4. Charge-Discharge System

4.1 System

The schematic diagram of charge and discharge system for studying momentary voltage drop problems is shown in Figure 6. The system consists of the flywheel, the generating motor, a power amplifier, a tachometer, an AD/DA converter, personal computer (PC) for control, a momentary voltage drop simulator, some relays, and a load (20Ω). In addition, the voltage to the load is supplied with DC voltage to easily calculate the electrical energy and the amount of saved energy.

The momentary voltage drop is simulated by reducing the power supply voltage from 5V to 3V for a short period of time using the voltage drop simulator. In the experiment, 100ms is set for period of the momentary voltage drop. The power supply voltage is always monitored by the PC. When the system is in normal condition, the system supplies electric power to the load and charges electric energy in the flywheel. The order of the charge is given from the PC through the power amplifier to drive the generating motor. The rotational speed of the flywheel is detected by the tachometer and the amount of energy can be monitored. The amount of energy is adjusted by increasing and decreasing the rotational speed to keep the rotational speed constant.

4.2 Generating Motor

The generating motor consists of 2-phase 4-poles brush-less DC motor and a Hall sensor. As shown in Figure 1, the magnet installed in the upper part of the flywheel is used as a rotor of the DC motor. It is possible to turning flywheel and to generating electricity from flywheel rotational.

The gap between magnet and electromagnets of the rotor is set at 1.0mm. The magnet for generating motor uses ring type, one side 4 poles, both side 8 poles, dimension Φ48xΦ25x3.5mm, neodymium magnet with Ni plating, and magnetic flux density 0.25T.

The rotary excitation pattern for the generating motor is shown in Figure 7. In this experiment, one method of excitation pattern were tested for driving the generating motor. When the Hall sensor detects S pole, coil X2 and Y2 excite the S pole and coil X1 and Y1 excite the N pole. In addition,

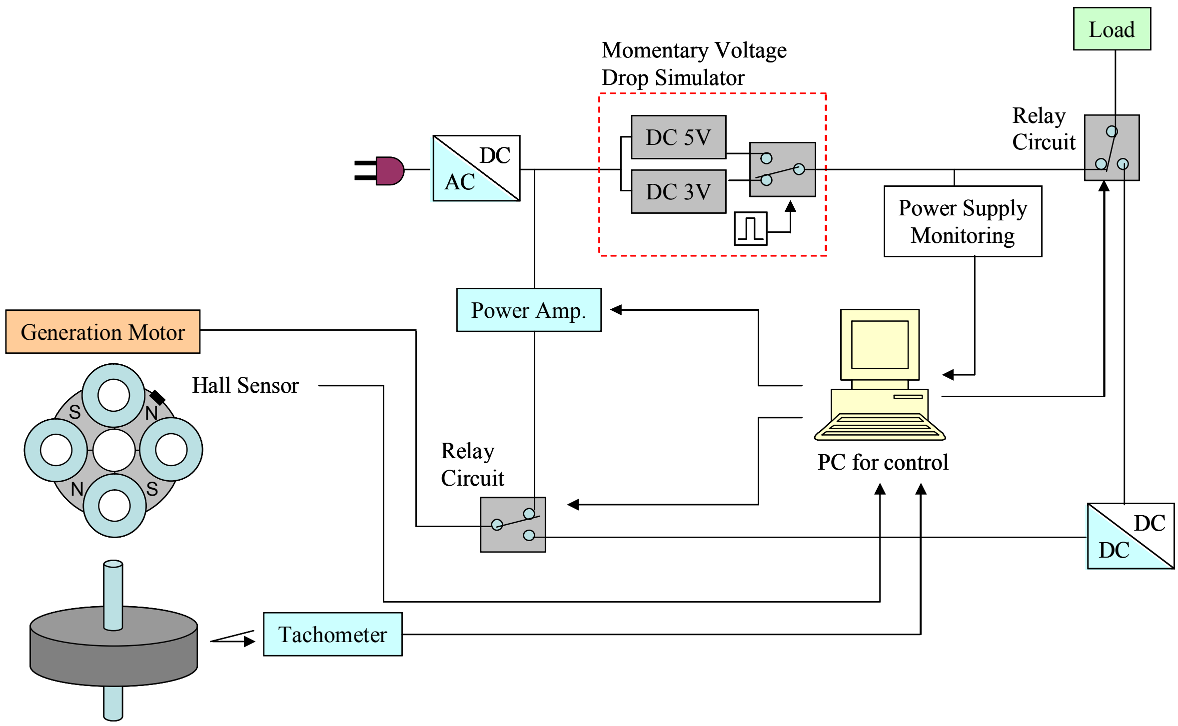


Fig.6 System for momentary voltage drop

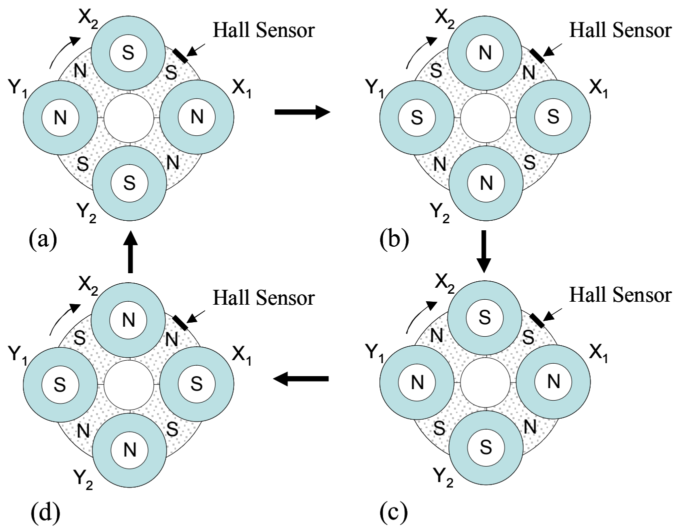


Fig.7 Exciting pattern of the motor

the each of coils excites the reverse poles when the Hall sensor detects N pole. In this manner, the rotor of N and S poles can be attracted at the same time which plans to increase the rotational speed.

A rectifier circuit is used for generating electric power. The electric power is in proportion to the rotational speed. Therefore, switching regulator is used to get constant output of 5V.

5. Experiment Result

5.1 Free-run

Figure 8 shows rotational speed and vibration characteristics at the top and the bottom of flywheel. Except the resonance area, the vibrations occur at the top of flywheel around 0.30mm$_{o\text{-}p}$

and at the bottom of flywheel around 0.25mm$_{o\text{-}p}$. As shown in Figure 8, the free-run time from the speed 5000rpm has about 40s. Concerning the vibration characteristic, the resonance occurs between 2,500~3,500rpm. However, the vibration near SMB is considerably suppressed. From the structure of this experimental machine, the gap between the rotor and the stator at the PMB is around 5mm, but the gap between the rotor and the stator at the SMB is only around 0.5mm.

5.2 Improvement on Generating Motor

The magnetic flux density that occur at the coil, is measured depend of the current coil and winding numbers. This measurement is done to select which the coil to be effective to increasing the rotational speed. Figure 9(a) and 9(b) show measurement result of the magnetic flux at coils with numbers of turns 400, 500 and 650 by (a) parallel and (b) serial connection. The coils are supplied by limited voltage 15.0V and adjusted current.

Figure 10 shows the experiment result using the coil, numbers of turns 500, by serial and parallel connection. As shown in Figure 10, the rotational speed with parallel connection is around 6,000rpm, that higher than the rotational speed with serial connection 3,600rpm.

The driving program of generating motor has been improved to increase the rotational speed. On the original program before improvement, if the Hall sensor detects from N pole to S pole or opposite, the driving program quickly respond to excite coils by changing direction of exciting coils. However, the current can not be flowed quickly in this time when rotational speed is high, because coils have the electromotive force. Therefore, the improvement program was done by creating space to make the electromagnet is not energized at N-S poles area. This improvement program was tested. Figure 11 shows the experiment result before and after improvement by various ranges.

As shown in Figure 11, the rotational speed with program before improvement is around 5,200rpm and average rotational speed after improvement is around 5,520rpm. Comparing with the previous program, the rotational speed after improvement increased around 6%.

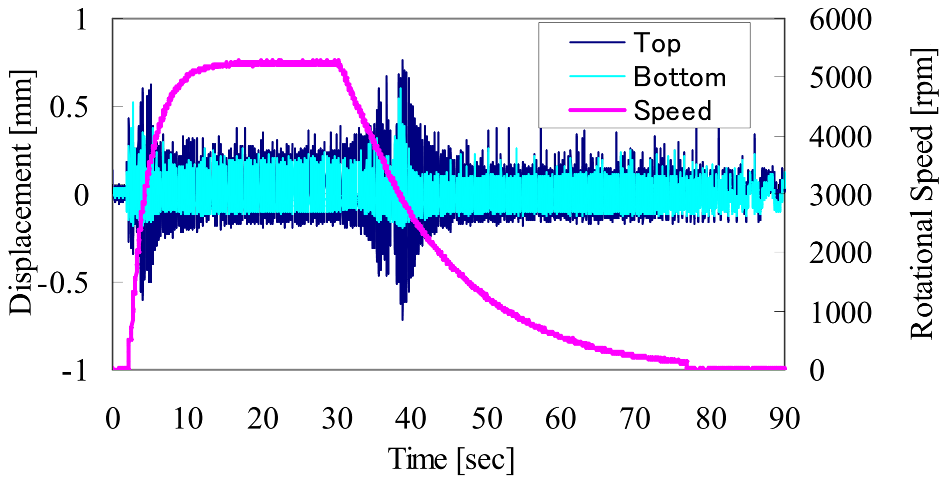
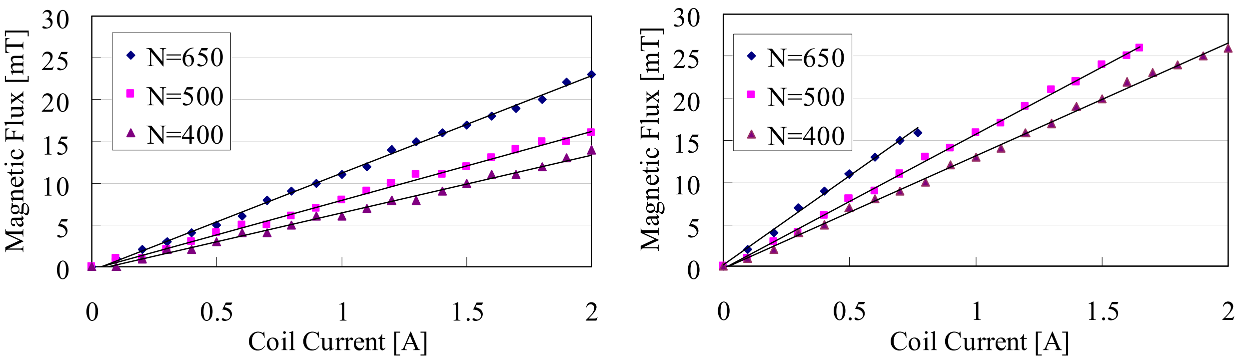


Fig.8 Rotational speed and vibration characteristics



(a) Parallel connection (b) Serial connection

Fig.9 Result measurement of magnetic flux at coils

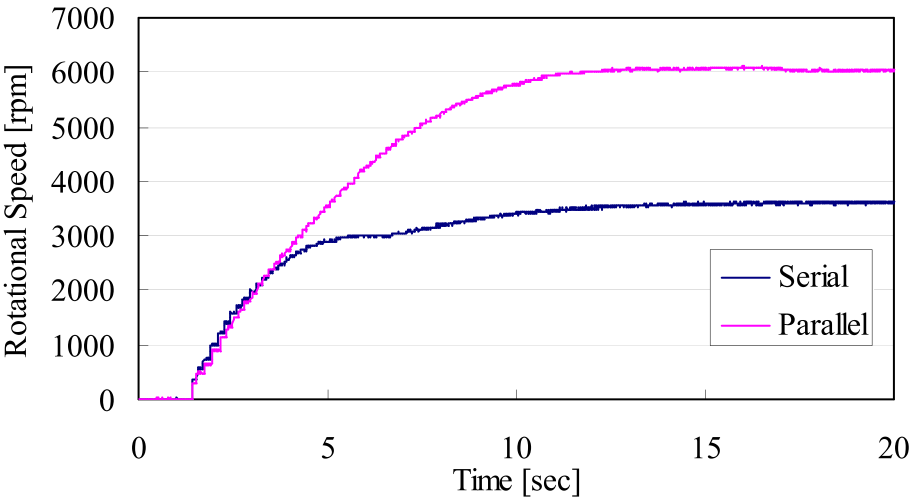


Fig.10 Experiment result using serial and parallel connection

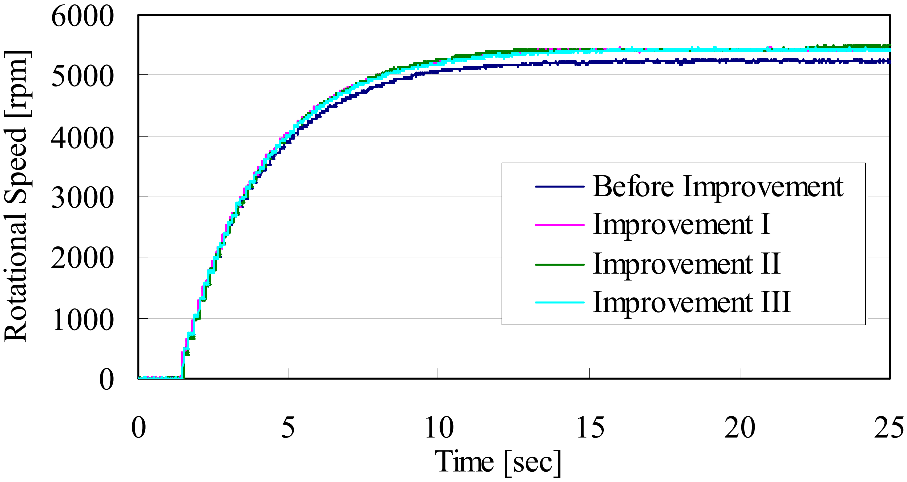


Fig.11 Experiment result before and after improvement

5.3 Energy discharge of momentary voltage drop

The experiments of momentary voltage drops were performed. In the experiments, the voltage of power supply suddenly changed from 5V to 3V. Then, the dynamic characteristic of the system were measured. The experimental result of discharge system is shown in Figure 12, indicating (a) power supply voltage, (b) load voltage, (c) rotational speed, (d) displacement, and (e) flywheel energy. As shown in Figure 12(a), the momentary voltage drop is 3V for 100ms. The load voltage falls to 0V because the relay circuit needs switching time. The time between voltage drops and the load voltage recovers again is about 8ms, but it is not a problem because the temporary blackout time is shorter than 15ms. The rotational speed decreases only at period of the flywheel energy supplied to the load as shown in Figure 12(c). When the power supply voltage drops, the relay switches the connection from charge to discharge system and switches the connection to the

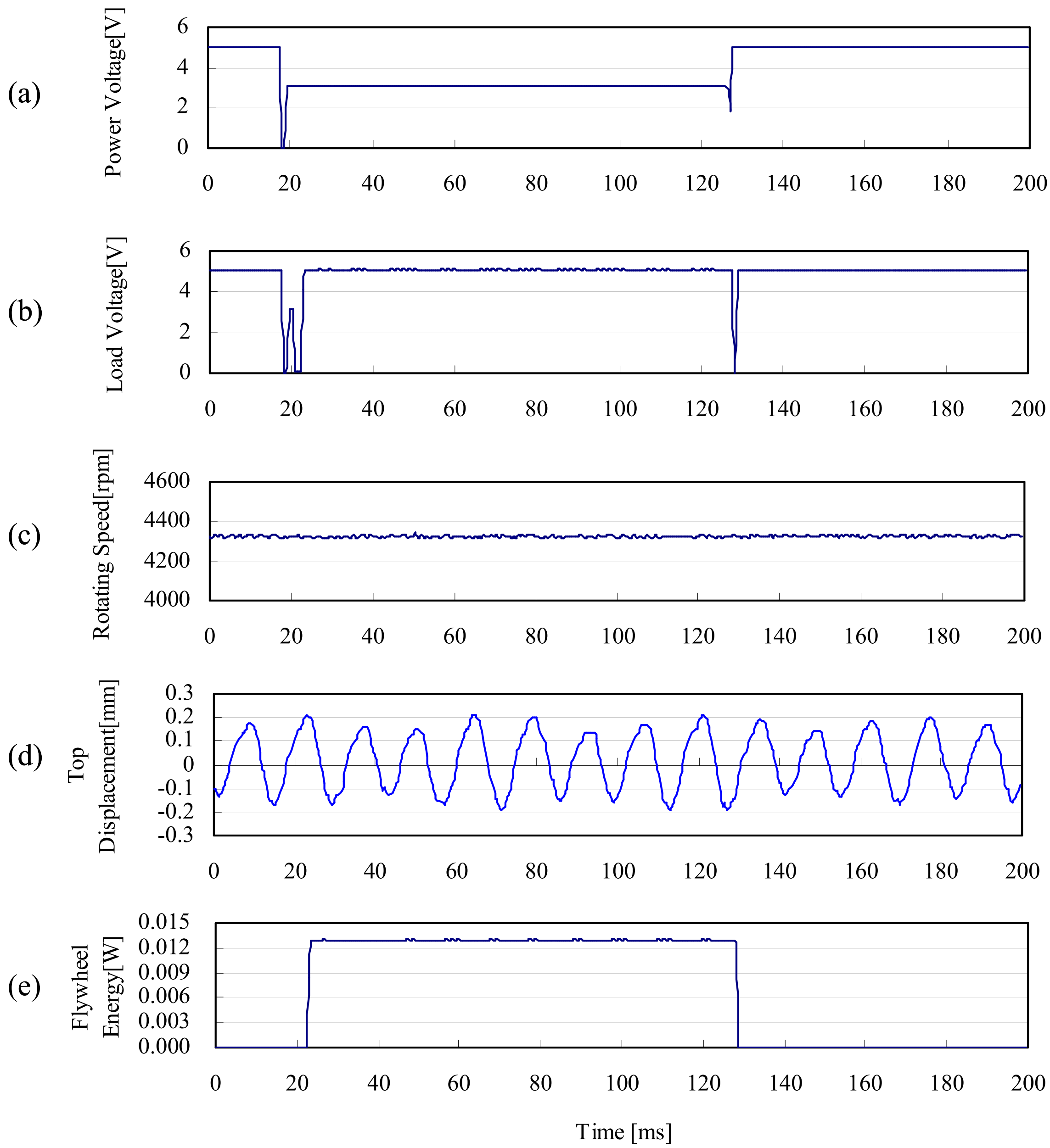


Fig.12 Flywheel characteristic at the time of momentary voltage drop

converter. The rotational speed does not decrease so much because the period of voltage drop is too short. When the power supply voltage returns, the load is possibly connected to the power supply. Then, the rotational speed increases and the charge system works again. The system can be confirmed that the displacement of the rotor does not change at the period switch of the charge/discharge and works as a stable system.

Anyhow, it is confirmed that the stored energy in the flywheel can be discharged and supplied to the load when momentary voltage drops occur.

6. Conclusion

The improvement of driving program for generating motor was done to increase the speed rotating of compact energy storage flywheel system that uses a superconducting magnetic bearing (SMB) and a permanent magnet bearing (PMB). Comparing about connection between coils, the rotational speed with parallel connection 6,000rpm is higher than with serial connection 3,600rpm. Comparing with the previous program, the rotational speed after improvement increased around 6%. The SMB suppresses the vibrations of the flywheel rotor. The PMB is used as passive type of bearing. The experimental results show that the displacements in top and bottom of flywheel are smaller than 0.30mm and 0.25mm in the speed range, except for the resonance rotational speed.

The experiments of momentary voltage drops were performed. In the experiments, power supply voltage, load voltage, rotational speed, displacement and supply were measured. The results show that the stored energy in the flywheel can be discharged and supplied to the load when momentary voltage drops occur.

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