Flywheel Energy Storage System with Superconducting Magnetic Bearing

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In an effort to level electricity demand between day and night, we have carried out research activities on a high-temperature superconducting flywheel energy storage system (an SFES) that can regulate rotary energy stored in the flywheel in a noncontact, low-loss condition using superconductor assemblies for a magnetic bearing. These studies are being conducted under a Japanese national project (sponsored by the Agency of Industrial Science and Technology - a unit of the Ministry of International Trade and Industry - and the New Energy and Industrial Technology Development Organization). Phase 1 of the project was carried out on a five-year plan beginning in fiscal 1995 with the participation of 10 interested companies, including Shikoku Research Institute Inc.

During the five-year period, we carried out two major studies - one on the operation of a small flywheel system (built as a small-scale model) and the other on superconducting magnetic bearings as an elemental technology for a 10-kWh energy storage system. Of the results achieved in Phase 1 of the project (from October 1995 through March 2000), this paper gives an outline of the small flywheel system (having an energy storage capacity of 0.5 kWh) and reports on progress in the development of magnetic bearings using superconductor assemblies (which we call "superconducting magnetic bearings" or "SMBs").

1. Small-Scale Model

1.1. System Configuration

The small-scale model was built in 1998 mainly for the purpose of demonstrating a control technology for high-speed operation of a rotor levitated in a noncontact condition by a superconducting magnetic bearing. In a series of tests on the system model, the rotor attained a rated operating speed of 30,000 rpm in the condition of completely noncontact magnetic levitation. At the rated speed of 30,000 rpm, the rotor gave the system an energy storage capacity of 0.5 kWh [1].

Major components of the system include a superconducting magnetic bearing, flywheels, active magnetic bearings and a motor generator. Figure 1 shows the system configuration of the small-scale model.

The two flywheels were carbon-fiber-reinforced plastic (CFRP) components, each measuring 400 mm in diameter and 40 mm in thickness and weighing 4.9 kg. One of them was installed at the top of the main rotor shaft and the other at the bottom. The whole rotor assembly, including the main shaft, had a total weight of 37 kg.

For this model, we used an axial-type superconducting magnetic bearing (AxSMB) to support full 37 kg of the weight of the rotor assembly during rotation. The AxSMB consisted of a superconductor assembly on the stationary side and a permanent magnet assembly on the rotor side, of which the superconductor assembly was prepared by putting YBCO high-temperature

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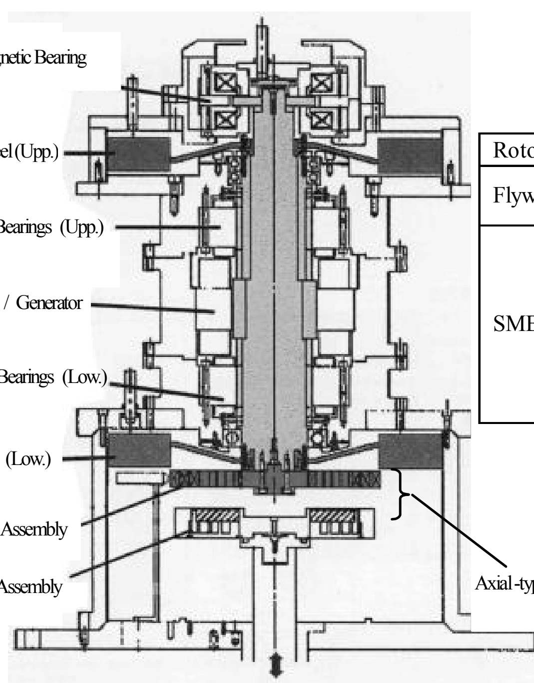
superconductors into a stainless steel container. The high-temperature superconductors were cooled to - 196℃ by liquid nitrogen supplied from an external source. Meanwhile, the permanent magnet assembly was prepared by coaxial arrangement of four radially-magnetized, ring-shaped magnets in such a way that they had the same poles opposed to each other with an iron yoke in between. The periphery of the magnet assembly, which had an outer diameter of 180 mm, was strengthened with CFRP so that it could withstand the centrifugal force of rotation.

Four active magnetic bearings were installed in the radial direction and one in the axial direction to provide the system with noncontact vibration-reducing capability during the rotation of the rotor. In addition, the rotating shaft was equipped with two emergency touchdown bearings, one on the top end and the other on the bottom end, as a protection against an impact from emergency system shutdown. The touchdown bearings were installed in case the active magnetic bearings should fail to work properly and, as such, they were left out of contact with the shaft at normal times.

The motor generator, a 2-kW unit, was installed in the middle of the rotating shaft to operate an energy input and output device.

All system components described above were housed in a vacuum chamber which was provided with a special device to keep the inside vacuum to reduce windage losses.

In building the small-scale model, the design and fabrication of the total system and rotation controls were undertaken by Koyo Seiko. Among major system components, the flywheels were supplied by Ishikawajima-Harima Heavy Industries, the rotating permanent magnet assembly by Seiko Epson, and the superconductor assembly by Nippon Steel Corporation. Shikoku Research Institute took charge of designing and fabricating the superconducting magnetic bearing and studying the operation of the finished small-scale model.



Rotor weight	37kg
Flywheels	CFRP : Weight : 4.9kg ×2 400mm od.- 250mm id.,×40mm h.,×2
SMB	Axial type ・ring-shaped permanent magnet NdFeB assembly 180mm od.- 96mm id.,×20mm h. ・high-temperature superconductor YBCO assembly 204mm od.- 84mm id.,×15mm h.

Figure1. Structure of the small-scall model

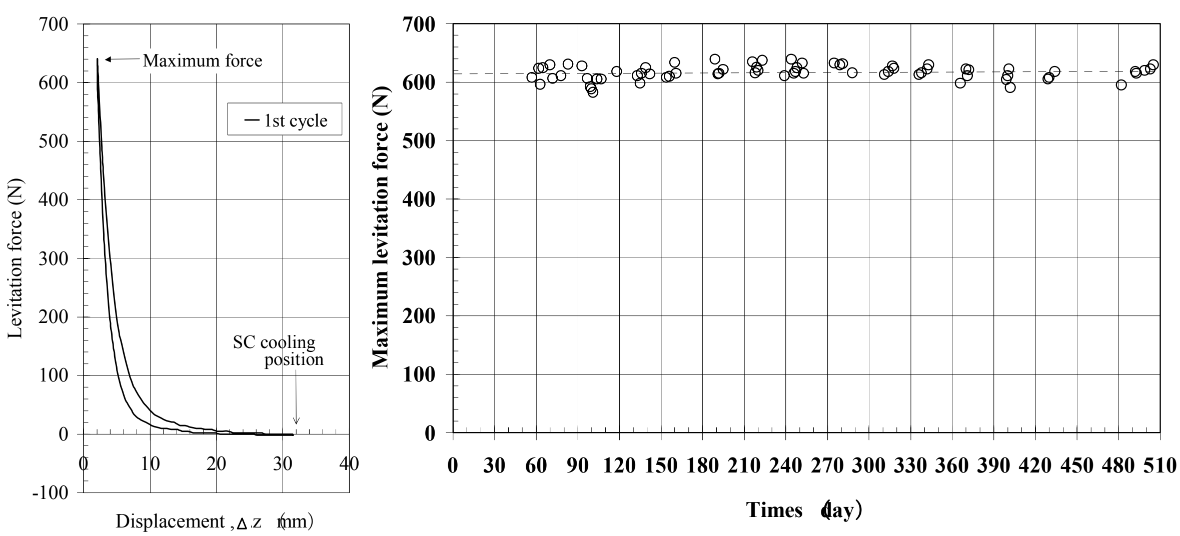
1.2. Operational Test

We conducted an operational study of the small-scale model for 17-months from July 1998 to November 1999. The model was provided with a steel protective cover and installed in a semi-underground test pit. Its operation was monitored from an operation control room outside the test pit. According to the data recorded during the study, the total operating time of the system reached 1,110 hours, the total cycles of starts and stops came up to 196, and the total operating time of the superconducting magnetic bearing came to 3,659 hours.

Now let me summarize the aging degradation characteristics of the superconducting magnetic bearing and the results of a active magnetic bearing test and free-run test.

(1) Aging Degradation Characteristics of the Superconducting Magnetic Bearing

We assessed the degree of decline in the levitational capability of the superconducting magnetic bearing to examine how far its superconductor assembly would be degraded by rotor weight supporting and repeated thermal stress resulting from cooling and heating. For this assessment, the maximum levitation force of the superconducting magnetic bearing as installed in the small system was measured during the operational study, with the gap between the superconductor and permanent magnet assemblies reduced to 2 mm after the superconductor assembly was cooled at a gap of 32 mm. When the gap was reduced, the axial-type superconducting magnetic bearing (AxSMB) generated a magnetic levitation force as shown in Figure 2(a). The results of examining the aging degradation of the maximum levitation force are summarized in Figure 2(b). During this period, the AxSMB maintained a sufficient magnetic levitation force to support the rotor assembly which weighed 37 kg. Although the maximum levitation force varied somewhat, no appreciable degradation of the AxSMB was found as its magnetic levitation force did not tend to decline on the whole. During the measuring period, the frequency of heat cycles in the AxSMB (i.e., the frequency of rises and falls in the temperature of the superconductor assembly) was increased to accelerate the aging degradation of the assembly due chiefly to thermal stress. The heat cycles of the bearing totaled 292 during the period.



(a) Levitation force characteristics

(b) Aging degradation of levitation force

Figure 2. Magnetic Levitation Force of AxSMB in Small-Scale Model

(2) Active Magnetic Bearing Test

Active magnetic bearings were installed in the system to provide noncontact vibration-reducing capability during the rotation of the rotor. A test on these bearings found that shaft vibrations increased somewhat when the operating speed of the rotor was raised from standstill to around 3,000 rpm, which was beyond the rigid body mode of rotor support, but the vibrations settled down to a steady state when the rotor speed rose above 7,000 rpm. This indicates that the rotor assembly could stably operate at high speed, holding down shaft vibrations to 30 μm or less over a full range up to the rated speed. During the operational study, no significant change was observed in the amplitude of shaft vibrations or in Lassajous figure of these vibrations at different operating speeds. The test findings prove that use of active magnetic bearings in combination with the superconducting magnetic bearing enables the rotor to operate stably in a noncontact condition for a long period of time.

(3) Free-Run Test (Energy Storage Efficiency Test)

A free-run test from 25,000 rpm was conducted on the model to determine rotation losses at selected operating speeds from the attenuation rate of revolving speed. The test found that the rotation loss caused by the active magnetic bearings was greater than expected and that the reduction of this rotation loss is a key factor in improving the efficiency of the energy storage system. In an efficiency test conducted in energy storage and discharge modes (with the rotor speed varied from 7,000 rpm to 25,000 rpm and then back to 7,000 rpm), the system was found to have a low storage efficiency of only 53% (recorded at the AC terminal with no standby time) as it was affected by the rotation loss stated above.

The small-scale model was built mainly to verify the serviceability of a system configuration that levitates a rotor by a superconducting magnetic bearing during high-speed operation. Accordingly we could not fully prove its performance as an energy storage system aimed at high efficiency, but many topics of future research and development were extracted from the model. Concerning improvement measures, including the reduction of the rotation loss caused by the active magnetic bearings, research activities are carried out separately as an elemental technology study which has already proved the feasibility of providing these improvement measures [2].

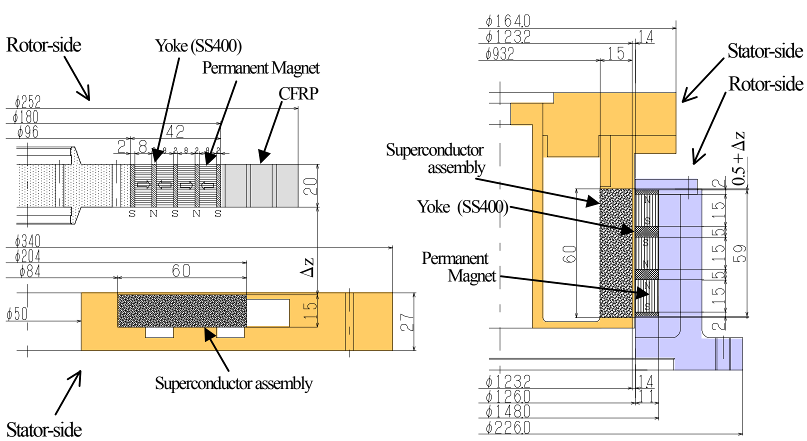
2. Manufacture of Prototype SMBs

We experimentally made an axial-type superconducting magnetic bearing for the small-scale model and a radial-type superconducting magnetic bearing for a 10-kWh energy storage system.

The axial-type SMB has a disk-shaped superconductor assembly and a permanent magnet assembly axially opposed to each other, as described earlier in this paper, and pushes up the rotor mainly by the repulsive force. The radial-type SMB is an outer rotor type bearing that suspends the rotor mainly the attraction between a cylindrical superconductor assembly (on the inner stationary side) and a permanent magnet assembly (on the outer rotor side) radially opposed to each other.

Expansion of the bearing area (i.e., the size of the surface at which the superconductor and magnet assemblies oppose each other) offers an effective tool to increase the magnetic levitation force of the bearing. But the outer diameter of the axial-type SMB can hardly be expanded because of problems concerning the mechanical strength of the rotary magnet assembly. In the small-scale model which was actually equipped with an axial-type SMB, the permanent magnet assembly was reinforced with CFRP but the maximum operating speed of the whole system was more severely restricted by the mechanical strength of the rotary magnet assembly than that of the flywheels themselves. Meanwhile, the bearing area of the radial-type SMB can be expanded by increasing its axial length and, consequently, the mechanical strength of the magnet assembly would be less affected by the expansion. This means that the radial-type SMB is more suitable for larger energy storage systems that will be built in the years ahead.

Taking these factors into account, we made an experimental radial-type SMB using approximately the same quantities of superconductors and permanent magnets as those of the axial-type SMB that was installed in the small-scale model. Then we measured the magnetic levitation force of the radial-type SMB thus prepared. Figure 3 briefly describes the structure of the axial-type and radial-type SMBs, and Figure 4 shows the measured magnetic levitation force of the radial-type SMB. Compared with the axial-type SMB used for the small-scale model, according to the measurement, the radial-type SMB could generate a greater levitation force with a shorter displacement, achieving the maximum levitation force almost three times as large as that of the axial-type bearing. The measured values prove that the radial-type SMB has an advantage over the axial-type SMB in terms of magnetic levitation force as well.



(a) Axial-type SMB

(b) Radial-type SMB

Figure 3 Structure of φ180 mm SMBs

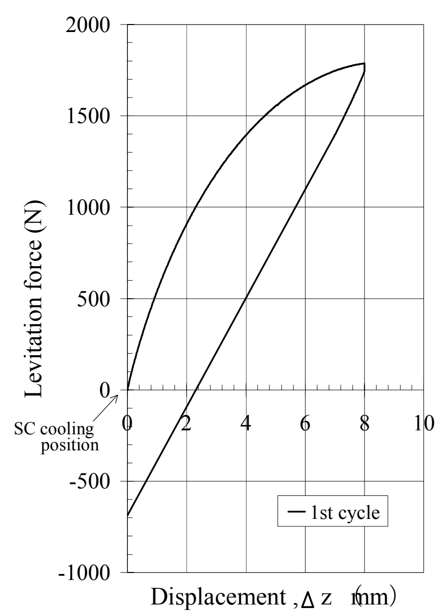


Figure 4 Levitation Force of φ180 mm Radial-Type SMB

3. Conclusions

From the operational study of the small-scale model, it was verified over a relatively long period of time that the proposed system could store energy by steady, high-speed rotation of the flywheels which were supported by a superconducting magnetic bearing. The study also extracted many topics of future research and development activities on flywheel energy storage systems. In addition, a separate study of elemental technologies proved the usefulness of radial-type SMBs for these systems. We are planing to have these results of the studies properly reflected in the development of elemental technologies which is being pushed on as a step toward the construction of larger, commercial energy storage systems in the years ahead.

Acknowledgement

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References

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