Development of Superconducting Magnetic Bearing Capable of Supporting Large Loads in Flywheel Energy Storage System for Railway Applications

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A superconducting magnetic bearing (SMB) has been developed with high temperature superconducting (HTS) coils and bulks for a flywheel energy storage system (FESS). The FESS equipped with the SMB was tested at the mega photovoltaic power plant test site in Yamanashi Prefecture. The SMB with both rotor and stator made of superconducting material, was capable of supporting the flywheel weighing 4000 kg without any contact and has so far remained in stable operation for 5000 hours. A further increase in storage capacity is required for the FESS to be applicable to railways as a system for preventing cancellation of regenerative braking. This paper describes the development of a SMB capable of supporting large 147 kN loads using a new type coil structure for the improvement of FESS storage capacity.

Keywords: flywheel, energy storage system, high temperature superconducting magnetic bearing, railway application, large load

1. Introduction

A FESS using SMB consisting of HTS coils and bulks, capable of suspending large loads stably without any contact has been developed [1]. The SMB, which is a contactless bearing, enables better maintainability which is the key problem faced with conventional flywheels because of conflict between bearings and mechanical losses. Flywheels using SMB have been under trial at the Komekurayama photovoltaic power test plant located in Kofu City, Yamanashi Prefecture since 2015 as a means to smooth electrical power output fluctuations in order to achieve a more stable power supply (Fig. 1, 2) [2]. The flywheel using SMB remained levitated for more than 5000 hours including plant tests, confirming the high reliability of SMB. Current trials are testing the reliability of SMB in experiments where they are subjected to 100 excitation cycles and 24 cooling cycles [3]. If FESS using SMB is to be applied to the railways to prevent cancellation of regenerative braking, the load that the SMB can supported must be raised, in order to increase storage capacity. This paper therefore reports on the design of a new superconducting coil fixed with a thermoplastic resin proposed by Railway Technical Research Institute, and the results of SMB levitation tests.

2. Underlying principles and characteristics of a superconducting flywheel energy storage system

Flywheel energy storage systems can store electricity in the form of kinetic energy by rotating a flywheel and converting the kinetic energy to the electric energy again on demand. A FESS does not deteriorate in the way of chemical cells due to repeated charging and discharging. Consequently, a FESS can be employed as a long-life storage system for applications requiring high frequency charging/discharging. For example, for an expected serviceable life of 30 years, the FESS must withstand several million or more charge/discharge cycles in order to effectively utilize the regenerative energy produced by electric railways or to moderate electrical power fluctuations from renewable energy sources, such as photovoltaic and wind power plants. As such, FESS is considered to be an option for such applications. The principles underlying a FESS are shown in Fig. 3. The stored energy $E$ [J] can be expressed in the following equation, where $M$ [kg] is the weight and $r$ [m] is the radius of the flywheel rotor, $\omega$ [rad/sec] is the
performance to secondary batteries or capacitors from a maintenance point of view. The solution to this problem is the SMB developed by RTRI where a strong magnetic repulsion force is used to levitate the flywheel eliminating contact and mechanical loss.

3. Results of experiments

3.1 Subheading limited to one line as much as possible

Figure 4 shows the HTS coils and bulks constituting the SMB. When the coils are excited, a powerful magnetic field is generated at the center of the coils. Then, the shielding current circulates across the surface of the HTS bulks, and a strong magnetic repulsive force is generated between the HTS coils and bulks. The SMB can support the weight of the flywheel rotor taking advantage of this force. HTS bulks in a rotor consist of one with a diameter of 140 mm and 20 mm thick, and two bulks 90 mm in diameter and 20 mm thick. The HTS bulks were manufactured by NIPPON STEEL & SUMITOMO METAL using the QMG (Quench and Melt Growth) method in such a way as to form a large disk [4, 5]. The HTS bulk with a diameter of 140 mm in the rotor supports the thrust load, while the two HTS bulks with a diameter of 90 mm function as a guide in the radial direction. The HTS coil as the stator is composed of five layers of double-pancake coil made with tape-shaped rare-earth HTS wires (manufactured by SuperPower) 6 mm in width and 0.1 mm thick coiled in the shape of a pancake with an outer diameter of 260 mm and inner diameter of 120 mm. Table 2 shows the design parameters of the HTS coils. To prevent the eddy current accompanying rotation, a “bamboo screen” structure cupper plate molded from thermoplastic resin is used for the cooling plate of the coils close to the HTS bulks [6]. Figure 5 shows the basic components in the SMB. The HTS coils are connected to a cryocooler and the HTS bulks are in a rotor. Helium gas is used to fill the inner vessel containing the SMB, and the pressure of the gas is designed to be in the pressure region (about 10 Pa) where the gas friction resistance (windage drag) is sufficiently small while heat transfer is large [7]. The HTS coils can be conductively cooled down while the HTS bulks are cooled by the helium gas. Therefore, it is a simple system that does not need a cryogen such as liquid nitrogen.

\[ E = \frac{1}{4} M(r_0)^2 \]  

Table 1 compares secondary batteries, capacitors and conventional flywheels. Since the output power and the storage capacity of secondary batteries and capacitors are closely related, they cannot be freely designed. On the other hand, the output power and the storage capacity of a FESS can be designed independently according to purpose because the storage capacity is defined from (1), and the output power is determined from the motor generator power. Furthermore, a FESS has the advantage that the rest of the storage capacity can be checked easily by monitoring the number of rotations, and if the rotation stops, the storage energy drops perfectly to zero. However, the large loads to be supported by the bearing in conventional FESS with mechanical bearings generates the need for large-scale maintenance. Based on this, a FESS would be inferior in

![Fig. 2 System configuration of prototype FESS](image)

![Fig. 3 Schematic representation of FESS operating principles](image)

**Table 1** Comparison between various types of batteries

<table>
<thead>
<tr>
<th>Item</th>
<th>Rechargeable Batteries</th>
<th>Capacitor</th>
<th>Flywheel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge rate</td>
<td>△</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Storage volume</td>
<td>○</td>
<td>△</td>
<td>○</td>
</tr>
<tr>
<td>Discharge rate</td>
<td>△</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Maintainability</td>
<td>○</td>
<td>○</td>
<td>△</td>
</tr>
</tbody>
</table>

![Fig. 4 HTS coils and bulks constituting SMB](image)
3.2 New HTS coils fixed with thermoplastic resin

Given that the storage capacity of the FESS for application to railways must be in the tens of kWh, it is important to be able to change the load supported by the SMB from 39.2 kN (as in the Komekurayama prototype) to 147 kN. A new coil was therefore designed and built, and fixed with a thermoplastic resin which can obtain a high current density and produce a large levitation force due to the improved winding space in the coils compared to conventional designs, and a test to verify the levitation force was conducted [8, 9]. Figure 6 shows the cross sectional areas of the new type coil component (b) compared to the conventional design (a). The conventional coil design used for the Komekurayama prototype (Fig. 6 (a)), has a double pancake coil encased in glass-fiber reinforced plastic (GFRP) plate, and cooling plates are attached to the upper and lower sides. The heat transfer path is a high temperature superconducting wire - GFRP - cooling plate, and contact is maintained with each surface with compressive loads. In order to obtain more stable cooling, the cooling plate and the HTS wire should be fixed without inserting a thermal insulating layer such as GFRP between them. Therefore, the new coil design introduces a design which is the result of a developed actual HTS coil for Maglev. This means that the GFRP plate on the upper and lower surfaces of the conventional coil were replaced with a meshed copper plate while the HTS wire and the cooling plate were fixed with a thermoplastic resin to improve heat conductivity (Fig. 6 (b)) [10, 11]. In order to prevent the deformation and movement of the HTS wire, thermoplastic resin was also used for the GFRP plate in the coil. In the new coil structure, the gap between the double pancake coils was made smaller than in the conventional coil design, to make the coil structure compact and to obtain a high current density, i.e. generate a powerful levitation force.

3.3 Load tests using small-scale coil

In order to verify the manufacturability and load capacity of the new coil design, small-scale coils were produced for preliminary tests [8]. The specifications of the small-scale coil were 60 mm in inner diameter, 96 mm in outer diameter and 124 in number of turns, and SCS 6050-AP (6 mm wide wire made by SuperPower Co., Ltd.) was used for the HTS wire. The critical current (Ic) of the small-scale coil was measured in liquid nitrogen. In order to confirm that there was no deterioration in the coil during the production process, the coil was excited before and after the thermoplastic resin fixation process. After checking the coil, a load test was carried out with a compression tester. Figure 7 shows the schematic illustration of the compression test. The compression test was conducted with the coil excited, and the voltage change between both the ends of the coil was measured. A new coil design fixed with the thermoplastic resin and using the same specifications as the Komekurayama prototype was selected, based on the following confirmations: Namely, no change in critical current due to compressive loads and no damage to the structural members, improvement of cooling by copper interdiction material, no significant change in the critical current of the superconducting coil even under a load of 50 kN (same level as the Komekurayama prototype), and no visible damage.

Table 2  Design parameters of HTS coil

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tr>
<td>HTS wire</td>
<td>RE-Ba-Cu-O</td>
</tr>
<tr>
<td>Width of wire</td>
<td>6 mm</td>
</tr>
<tr>
<td>Thickness of wire</td>
<td>0.1 mm</td>
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<tr>
<td>Inner diameter of coil</td>
<td>120 mm</td>
</tr>
<tr>
<td>Outer diameter of coil</td>
<td>260 mm</td>
</tr>
<tr>
<td>Thickness of double pancake coil</td>
<td>17.6 mm</td>
</tr>
<tr>
<td>Number of double pancake coil</td>
<td>5</td>
</tr>
<tr>
<td>Inductance of coils</td>
<td>4 H</td>
</tr>
</tbody>
</table>

Fig. 6  Cross sectional areas of new type coil component (b) compared to conventional design (a)

Fig. 7  Schematic illustration of compression test

4. Levitation force test [12]

4.1 Coil configuration and load factor prediction

In designing the new coil fixed with the thermoplastic resin, the arrangement of the wires to be used was examined so that the load factor during the excitation was at most 60%. From the electromagnetic force analysis, when the exciting current of the HTS coil was 160 A, the lev-
4.2 Levitation force test exceeding 147 kN

Figure 9 shows the appearance of the new coil fixed with the thermoplastic resin, and Fig. 10 shows the experimental setup of the levitation force test. The levitation force generated between the HTS coils and bulks was measured by a load cell installed on the upper part (atmosphere side) of the test apparatus. The thermal insulation shaft with the built-in HTS bulk had the same specifications as the Komukayama prototype and was subjected to a levitation force of 98 kN. The repulsive force between the HTS coil and the bulk was supported by the outer vessel container via four thermal insulation supports, described later. In the dilute helium gas atmosphere, the HTS coils and bulks were brought to the predetermined temperature by the cryocooler, and then the HTS coils were excited. Figure 11 shows the relationship between the excitation current and the generated levitation force, together with that obtained from the calculation and that at the time of the 98 kN test. The levitation force was in equilibrium with the atmospheric pressure load (0.93 kN) when the applied current exceeded 25 A, and in the region above 25 A, the levitation force increased almost by the square of the applied current, and the levitation force of the target value of 147 kN was obtained when the applied current was 160 A. The reason for the difference with the calculated value was considered to be the influence of the magnetic flux penetration into the HTS bulks. After the levitation test, a visual inspection of the HTS coil was carried out, which confirmed that there was no change in the HTS coil characteristics. It is deemed that these results prove that the SMB for large load using the new HTS coils fixed with thermoplastic resin, are suitable for manufacture.

5. Thermal insulation supports

The appearance of the thermal insulation supports is shown in Fig. 12. Since the thermal insulation support transmits the levitation force applied to the low-temperature vessel of the SMB to the part at room temperature, compatibility between the thermal insulation properties and the load bearing characteristics is necessary. For this reason, alumina fiber reinforced plastic (AFRP), which has excellent thermal insulation properties and high tensile

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**Fig. 8** Load factor distribution predicted at coil temperature of 30 K

**Fig. 9** Internal structure of HTS coil and appearance of new coil design fixed with thermoplastic resin

**Fig. 10** Experimental setup of levitation force test

**Fig. 11** Relationship between excitation current and generated levitation force
strength, was adopted. When the levitation force was 147 kN, the reaction force of each thermal insulation support was 36.8 kN. After confirming that the thermal insulation support could be used in an elastic deformation region up to 98 kN with a safety factor of more than 2 [13], the thermal insulation supports were incorporated into the levitation force test apparatus. Figure 13 shows the state of the tensile test of the thermal insulation support. The strain gauge was attached in the center of the AFRP rod. Figure 14 shows the tensile test results of the thermal insulation support before and after the levitation force tests. When the maximum tensile force was 49 kN, the elastic modulus of the AFRP was about 42 GPa as seen from the stress strain diagram and the maximum stress of the tensile test was 110 MPa. It was confirmed that the characteristics of the thermal insulation support did not change even after the levitation force test of 147 kN [14]. Basic data will be collected on the reliability of the thermal insulation support, which is an important component of the SMB, by evaluating the strength (fracture strength) of the AFRP rod and repeated tensile load tests corresponding to the SMB’s expected life of 30 years.

6. Conclusions

Given that the storage capacity of the FESS for application to railways must be in the tens of kWh, it is important to be able to change the load supported by the SMB from 39.2 kN (as in the Komekurayama prototype) to 147 kN. A new HTS coil design was therefore developed, fixed with thermoplastic resin, drawing on the results from development work on actual sized HTS coils for Maglev, and SMB levitation force tests were conducted. The new HTS coil was incorporated into levitation force test apparatus; the HTS coils and bulks were then brought to the predetermined temperature by the cryocooler, and the superconducting coil was excited. The target 147 kN levitation force was obtained when the current applied was 160 A. After the levitation test, a visual inspection of the superconducting bulk and excitation tests on a single coil were carried out, confirming that there was no change in the superconducting coil characteristics. These results seem to prove the constructability of the SMB for large loads using the new superconducting coil fixed with thermoplastic resin. The thermal insulation support was also designed to be capable of bearing a large load of 147 kN. The thermal insulation supports were incorporated into the levitation force test apparatus and subjected to levitation force tests. Tensile load tests were carried out before and after the levitation force tests confirming that there were no changes to the characteristics. The reliability of the SMB and the thermal insulation support will be further checked through repeated excitation tests, continuous levitation tests etc., to reflect actual operational conditions and assuming a serviceable life of 30 years.

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