Development of Superconducting Magnetic Bearing for Flywheel Energy Storage System

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ABSTRACT Because of a large demand of a low carbon society, the dependence rate on renewable power sources, such as solar power generators and wind power generators, is increasing. A flywheel energy storage system, which can charge and discharge the electrical power rapidly has been developed, in combination with the development of the unstable renewable power source, in order to stabilize a power system and a regenerative power recovery system of a rail system in The New Energy and Industrial Technology Development (NEDO) project. The flywheel energy system charges electrical power from the kinetic energy of a rotating flywheel, and discharges the power transforming the kinetic energy back into electrical power. Furukawa Electric developed a superconducting magnetic bearing (SMB) combining a Rare Earth $Ba_2Cu_3O_y$ (REBCO) high temperature superconducting coil with a high temperature superconducting bulk, and succeeded to achieve a non-contact levitation and a non-contact rotation of a rotor of 4 tons. In this paper, a design process, a trial manufacturing and a performance test of the SMB are reported.

1. INTRODUCTION

Furukawa Electric has been developing a flywheel (FW) energy storage system in the NEDO project of the development of a next generation flywheel energy storage in cooperation with the Railway Technical Research Institute, Yamanashi Prefecture Government, Kubotek Corporation and MIRAPRO Co. Ltd.[1), 2)]. A verification test facility has been established and the test of the flywheel storage system is proceeding with the photovoltaic power station located in Mt. Komekura of the Yamanashi prefecture in Japan.

The FW energy storage system charges the electrical power from the kinetic energy of a rotor. Since the FW system is not deteriorated chemically from the electrical charge or discharge compared to a secondary battery, it has a long stable operating life. The storage capacity and the output power of the second battery are determined on the battery size, and we need a large capacity of the secondary battery to obtain a large power. However, it is possible for the FW energy storage system to design a rotor size and an output power of an electric motor generator independently. It is possible to have various combination of high power with small capacity or low power with large capacity. Furthermore, it has more advantage in checking remained energy and is free from harmful wastes[3), 4)]. The verification apparatus for the project is one of the largest in the world, it has a capacity of 100 kWh, rotor (2 m of a diameter), a weight of 4 ton and a rotational speed between 3000 rpm and 6000 rpm at acceleration-deceleration, and at charge-discharge. Further, a flagship model design (future equipment model) with a capacity of 300 kWh and a levitation of rotor weight of 10 ton was achieved.

Furukawa Electric was responsible for the development of the superconducting magnetic bearing (SMB).

The purpose of the use of the SMB to apply levitation and rotation of the rotor is to prevent the energy loss from friction at the bearing and the maintenance cost from the mechanical abrasion.

The developed SMB consists of the REBCO (Rare Earth $Ba_2Cu_3O_y$) high temperature superconducting coil (superconducting coil) as stator and the REBCO superconducting bulk (superconducting bulk) as rotor, a repulsion force occurs when a shield effect of the superconducting bulk pushes away the magnetic field of the energized superconducting coil and the repulsion force is utilized as the levitation force.

Both of the stator and the rotor use the superconductor and a large mass of 4 tons is levitated. As the turning rotor has to be cooled under non-contact condition, the superconducting bulk is cooled with the heat transfer of a decompressed helium gas.

This paper reports a design and manufacturing of the SMB, a test result of the SMB itself and a performance of the SMB installed in the FW energy storage system.

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2. DESIGN OF THE SMB

The design of the SMB was targeting a levitation capability of 4 ton to 10 ton under the magnetic field created by the superconducting coil while keeping the structural stability against a reaction force on the levitation and a suitable cooling to the necessary superconducting current for the levitation. A basic design, a structural design and a heat transfer design of the superconducting coil are reported here.

2.1 Basic Design of the Superconducting Coil

The superconducting coil utilized in the SMB design is a double pancake coil, a combination of two of planar pancake coil windings of the superconducting wire, as a superconducting wire module. A stack of the superconducting coil module is used for the SMB. Figure 1 shows a photograph of the superconducting module and a picture of the SMB consisting of the superconducting coil module and the superconducting bulk.

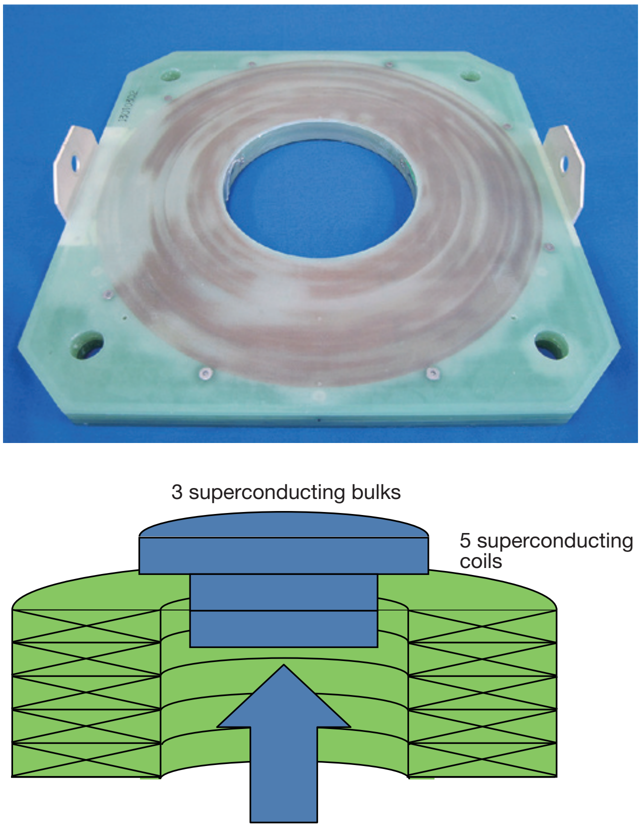

Figure 1 Superconducting module (Upper) and picture of the SMB (Lower).

The size of the superconducting bulk is determined to some extent because it is not easy for the superconducting bulk to grow in size. The design of the superconducting coil is related to the size of the superconducting bulk. At first the magnetic field necessary for the levitation was calculated on the basis of the superconducting bulk size, and the current turn number was obtained, and then the size of the superconducting coil was calculated. It was estimated that we need 5 superconducting coil modules combined with three of large or small superconducting bulks to obtain the levitation force of more than 4 ton for the 4 ton verification test. The reason we used two sizes of bulk was because the large superconducting bulk generated the levitation force by repulsion, and the small bulk entered into an inner diameter was used as a guide to keep in the center. The superconducting bulk and the superconducting coil are coaxial and if a displacement occurs, a construction to provide a force to push it back in a previous position is needed.

An electromagnetic analysis of the superconducting coil combined with the superconducting bulk was done with a levitation height of 20 mm with a coil current of 75 A. The result was shown in Figure 2. The calculation of the levitation force from the energizing coil current is shown in Figure 2. The levitation force is proportional to the square of the magnetic field [5), 6)]. The relationship between the coil current and the levitation force at the condition above is shown in Figure 3, and the coil current for the levitation force of 4 ton is 74 A.

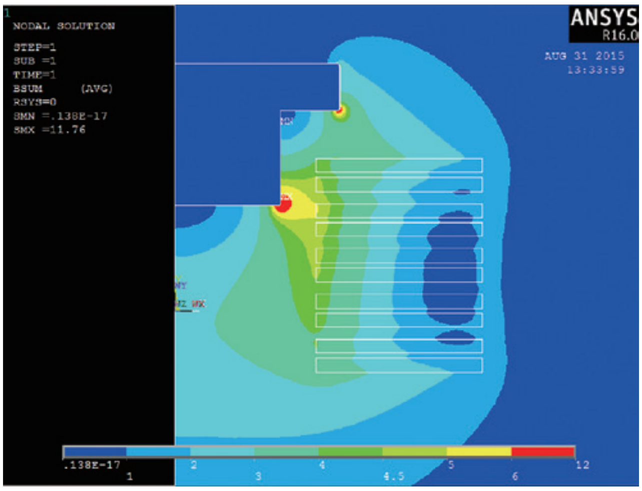

Figure 2 Electromagnetic analysis result for 5 superconducting coil modules and 3 superconducting bulks.

The superconducting wire has a limitation of the current without a resistance in the superconducting state which is called the critical current (I_c). The I_c is changed according to the temperature and the magnetic field as shown in Figure 4 (upper). The I_c is decreasing with the rise of the magnetic field for the same temperature, and the I_c is increasing with the decrease of the temperature for the same magnetic field. A maximum experimental magnetic field from the coil current in the superconducting coil is obtained according to the result of the electromagnetic analysis (Figure 2). When combining the result of the magnetic field with the I_c property of the superconducting wire, the I_c of the superconducting coil is obtained from the intersection point shown in Figure 4 (lower). The critical current of the superconducting coil was 98 A at 50 K from the Figure 5 and the value is more than the 74 A needed for the levitation. According to the result, it is expected that the superconducting coil was able to levitate 4 ton at 50 K.

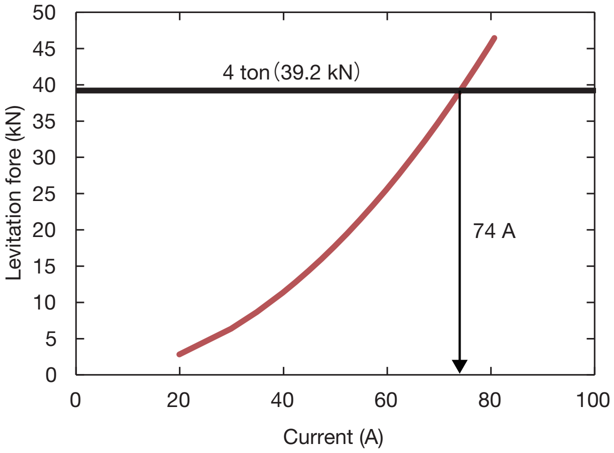

Figure 3 The levitation force dependence on the Current for 5 superconducting coil modules and 3 superconducting bulk.

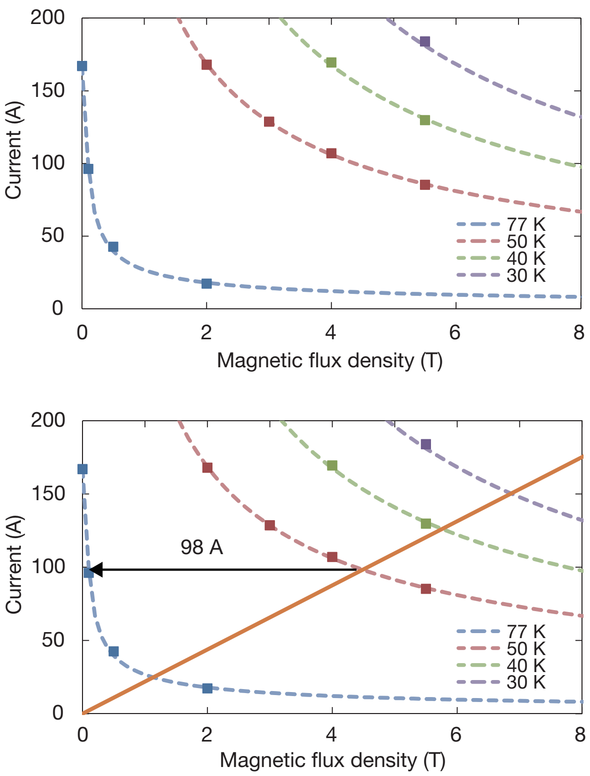

Figure 4 I_c (critical current) vs. B (magnetic flux density) of the superconducting wire at 50 K (upper), and I_c vs B of 5 superconducting coil modules at 50 K (lower).

And also, a final target of the project was the levitation of 10 ton of the rotor and the design of the superconducting coil for the levitation of 10 ton was achieved. Figure 5 shows the design of the SMB for the levitation of 10 ton, using seven (7) double pancake superconducting coils and four (4) superconducting bulk. In the case of 7 double pancake superconducting coils, the relationship between the coil current and the levitation force, and also the relationship between the coil current and the experimental magnetic field is shown in Figure 6.

The required coil current for the 10 ton levitation is 101 A. Since the I_c of the superconducting coil at 40 K is 116 A, it is expected to make a levitation of 10 ton at 40 K. Comparing with the levitation of 4 ton at 50 K, it needs decreasing the temperature of operation and increasing cooling cost for the levitation for 10 ton at 40 K. However the ability of the FW energy storage system of 10 ton is 2.5 times compared to the 4 ton levitation, we expect that the ratio of the cooling power to the output power will decrease.

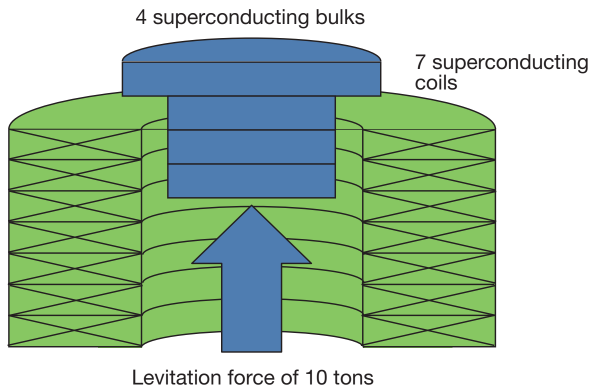

Figure 5 Picture of the SMB for the levitation of 10 tons.

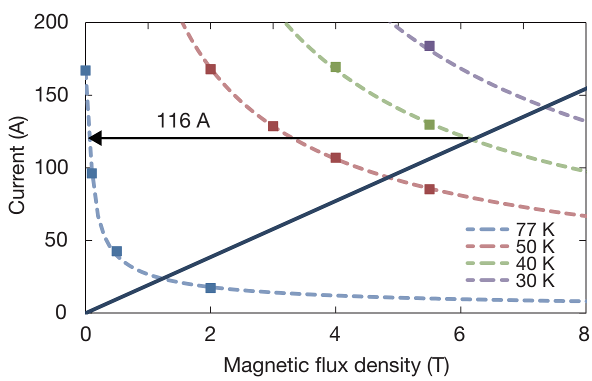

Figure 6 I_c property of Superconducting coil with 7 superconducting coil modules at 40 K.

2.2 Structural Design of Superconducting Coil

The superconducting coil receives a large reaction force to support a substantial load of the rotor. A structural design is made based on the assumed stress on the superconducting coil and checked the design through a structural analysis. The system in future is expected to be capable of levitation of a 10 tons rotor. The verification apparatus with yield strength of not only 4 tons but 10 tons was designed and checked through the structural analysis. The coil used is YOROI-coil (Y-based Oxide Superconductor and Reinforcing Outer Integrated coil) to maintain a high strength.[7)]

A structure of the SMB for the analysis is shown in Figure 7. The SMB has stacked 5 pieces of the superconducting coil module for the verification apparatus and stacked 7 pieces of the superconducting coil module for the future apparatus. A copper plate is tucked between the superconducting coil modules as a heat transfer plate. The double pancake coil has an inner cylinder made of FRP in its center part, the superconducting wire was looped around from the cylinder to the outer frame on the exterior. The analysis was done taking into consideration the above elements with a sole insert for the coil and paraffin impregnation between wires. The stress and displacement on various part of the structure was calculated based on the electromagnetic analysis result, and then magnitude of the displacement on various part was evaluated, and the stress and the durability of the material was checked. The displacement with the electromagnetic force for the future apparatus specification with the levitation of 10 tons was 0.17 mm and the result was not a severe problem. The value of the stress divided by the yield strength on various part is shown in Table 1. The result shows 15% at max, the design of the structure has enough yield strength. The result of the verification apparatus of the levitation of 4 tons, max displacement is 0.04 mm and the yield strength is 5.9% at max.

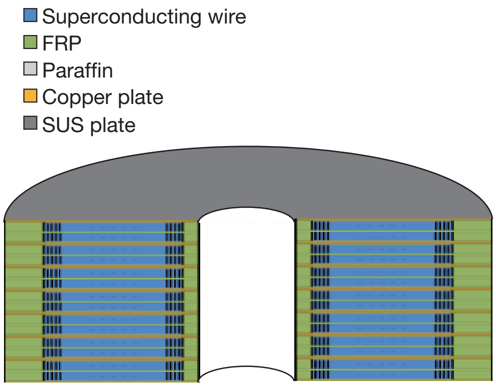

Figure 7 Conceptual diagram used for structural analysis.

Table 1 Load factor (Stress divided by yield strength) of various part.

Stress/Yield strength	Diameter direction	Axial direction	Circumferential direction
SUS plate (%)	1.1	2.1	2.3
Inner cylinder FRP (%)	13.1	3.2	1.7
External cylinder FRP (%)	3.2	8.2	1.7
Cover/Sole insert FRP (%)	8.5	1.7	2.0
Cupper plate (%)	15.1	8.0	4.4

2.3 Heat Transfer Design

The superconducting coil in the superconducting state operation has to be maintained at cold temperature and the target of the operation temperature is 30 K. We confirmed that the apparatus with 5 superconductor coils and three superconductor bulks obtained enough I_c for 4 tons of levitation described at article 2.1 in this paper. The system has enough room for heat control design, just as a contingency case, such as a refrigerator stops on an electric power failure of the flywheel, the system remains at 50 K and below to continue levitation for 30 min. until stopping of the rotor. The heat transfer design from the refrigerator to the coil part and the heat insulation design to reduce the heat penetration from the outside are important to cool the superconducting coil. Especially because the structure was robust to bear the load of 10 ton, it was necessary for the structure to have less heat penetration and to support the load at the same time.

The design of a cryostat with less heat penetration was successful based on a suitable bearing structure and a suitable selection of the material. The thermal analysis was done on the cryostat and the temperature of the superconducting coil and the superconducting bulk was estimated. The result is shown in Figure 8. The superconducting coil was cooled enough, the temperature of the coil was 17 K to 18 K, and also the heat transfer was maintained sufficiently, temperature distribution was within 1 K.

Since the temperature of the superconducting coil on the rotor side, cooled indirectly with helium gas, was around 22 K, we had a good cooling condition from the heat transfer of helium and a less heat penetration from outside according to the analysis. The superconducting coil and the superconducting bulk were able to be maintained at below 30 K and it proved the suitability of the design from the analysis.

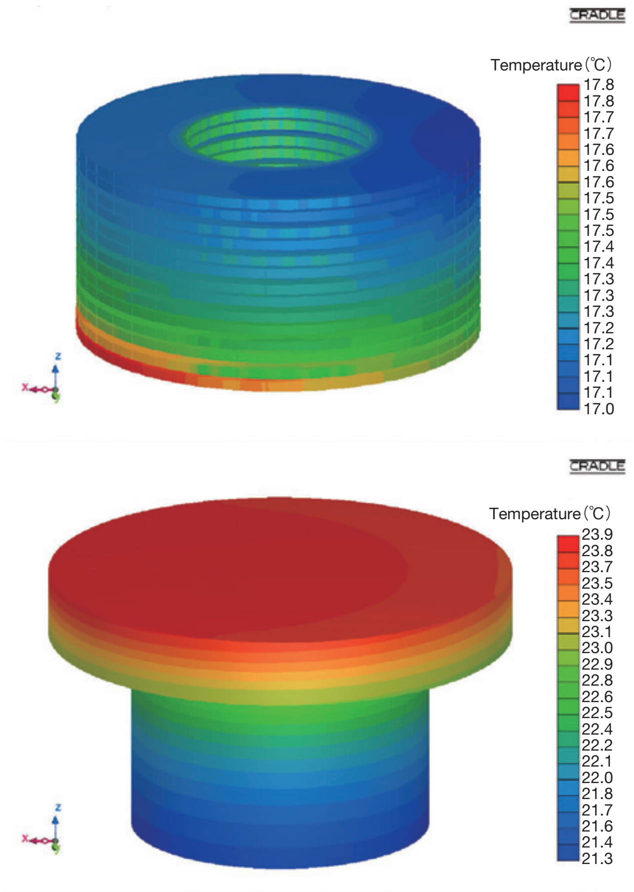

Figure 8 Temperature distribution through thermal analysis for the superconducting coil (upper) and the superconducting bulk (lower).

3. CURRENT TEST OF SUPERCONDUCTING COIL

A piece of the superconducting coil module is manufactured as a trial and we checked its performance before the actual manufacturing of the SMB. We checked a change of performance making the coil from the wire. A measured I_c was compared with the expected I_c from the electromagnetic analysis and we checked the precision of the analysis. The measurements of I_c in liquid nitrogen at 77 K and of I_c with the conduction cooling at 50 K were conducted.

3.1 I_c Measurement in Liquid Nitrogen at 77 K

The superconducting coil module was cooled gradually in the gasified nitrogen from liquid nitrogen at first and finally cooled down to 77 K in the liquid nitrogen and the I_c measurement was recorded. The current flows in the superconducting coil with no resistance and the voltage is too small in the area of less than I_c. However the voltage loaded on the coil rises gradually with the increase of the current. In this report, I_c is defined the current when the voltage exceeds 70 μV. The coil has a reactance different from the wire and the change of the current generates the voltage.

The measurement of I_c on increasing current, the current increased to a certain value and maintained for a while at the value and the voltage at the current was measured. The result is shown in Figure 9. The voltage exceeded 70 μV at the current of 37 A and the obtained I_c was close to the analysis value of 36 A.

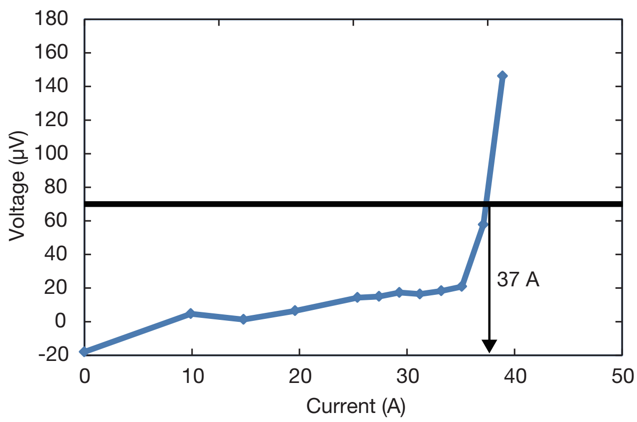

Figure 9 I_c test result of the superconducting coil module in Liquid Nitrogen at 77 K.

3.2 I_c Measurement at 50 K with conduction Cooling

The superconducting module was cooled to 50 K and I_c was measured. The cooling was a conduction cooling with a refrigerator, and the measurement was done in the cryostat prepared for the measurement with cooling. The temperature of 50 K was controlled to energize a heating wire installed in the refrigerator. As I_c measurement at low temperature with the conduction cooling has more current than the measurement at 77 K in the liquid nitrogen, and the heat generated from normal conductive part, such as a lead wire, and the heat generated from the coil reactance, and the heat generated when the voltage is increasing, on the other hand the no cooling effect with the latent heat through vaporizing of a coolant is expected, it is necessary to keep a constant temperature to maintain a high thermal conductivity. The measurement result of I_c for the coil at 50 K is shown in Figure 10. The voltage exceeded 70 μV at 160 A and I_c was 160 A. The result was similar to the analysis value of 149 A and the analysis was suitable.

The result is for one pieces of the superconducting module. The increasing number of the superconducting module affects I_c to decrease because the magnetic field increases. The I_c value obtained for 5 pieces of the superconducting module is 101 A from the analysis. The needed current was 74 A to levitate 4 tons according to the design and the analysis from the verification apparatus. The superconducting module had enough I_c for the levitation.

According to these results, the other coils and the cryostat to assemble with fly wheel system were made and the SMB was manufactured for trial.

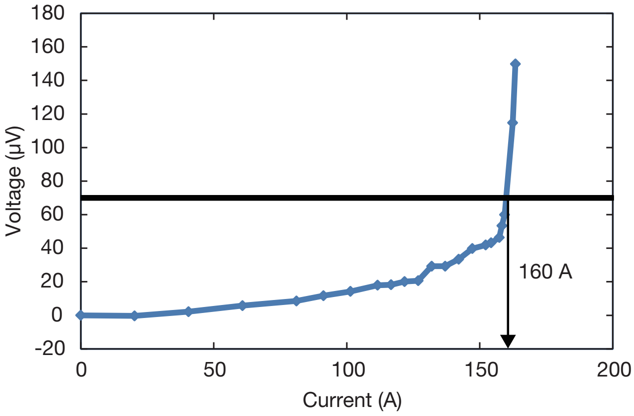

Figure 10 I_c **test result of superconducting coil module with conduction cooling at 50 K.**

4. CURRENT TEST OF THE SMB ITSELF

The superconducting coil assembled in the cryostat used as SMB for verification test, and combined with a shaft include the superconducting bulk, was done of cooling test and current loading test. The levitation force was measured for the current test. A stress, where a movable plate attached to the shaft pressed a load cell due to a reaction force from energizing, was measured. The levitation force was obtained from the stress, and it was checked against the levitation force of the 4 tons obtained from the verification test.

4.1 Cooling Test of the SMB

In the cooling test of the SMB, an outer tank for a vacuum thermal insulation and inside a coil container was vacuumed, and cooling began. When the coil was cooled, helium gas was introduced in the inside of the coil container and also the superconducting bulk was cooled. A cooling curve of the superconducting coil, the superconducting bulk and the other components is shown in Figure 11. After cooling the coil for 70 hours, the bulk cooling by helium gas began and the cooling was completed in 15 hours. The reason why the temperature decreases linearly is because, at high temperature the efficiency of the refrigerator is high and the heat capacity is also large, and on decreasing temperature, the efficiency of the refrigerator is decreasing and the heat capacity is decreasing. The superconducting coil is cooled finally to 18 K and the superconducting bulk is cooled to 22 K with introducing the helium gas. The result was satisfied with the target of the SMB operation temperature of below 30 K. The temperature is close to the result of the thermal conduction analysis. It shows that the conduction by helium and the thermal insulation efficiency on the rotor and the main body of cryostat are excellent, and it assumed that helium gas cooling has a good functional efficiency and the selection of a high thermal insulation material was successful.

It took 80 hours for cooling this time using only the refrigerator with no cooling medium, however the cooling time will decrease if we use some cooling medium, such as the liquid nitrogen, as a pre-cooling procedure.

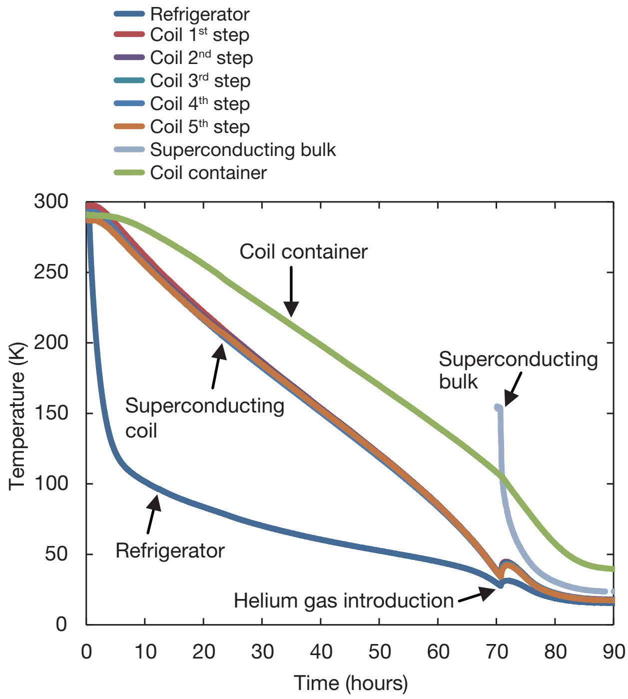

Figure 11 Cooling curve of superconducting coil and superconducting bulk.

4.2 Energizing Levitation Test

After succeeding of cooling the SMB, the superconduction coil was energized and the measurement of the levitation force was conducted.

At first, we checked whether the planned current was energized keeping the superconducting state, and whether we obtained the levitation force as same as the electromagnetic analysis result. The experiment was conducted at 30 K of a normal operation temperature and at 50 K of the maximum operation temperature.

4.2.1 Energizing levitation at 30 K

Even though the refrigerator could cool the superconducting coil to around 18 K, the test was carried out at a constant coil temperature of 30 K energizing a heater attached to the refrigerator. The relationship between the current and the measured levitation force, and the levitation force obtained from the analysis are shown in Figure 12.

The result suggested the levitation force of 4 tons (39.2 KN) at 76 A. The measured levitation force was close to the analysis value and the result defined the precision of the electromagnetic analysis. The measured value was lower than the analysis value, because the superconducting bulk cannot repel the flux completely and the flux entered a little into the bulk according to our speculation.

4.2.2 Energizing levitation at 50 K

As same as the test at 30 K, the energizing levitation test at 50 K of the coil temperature was performed by energizing the heater attached to the refrigerator. The relationship between the measured levitation force and the current is shown in Figure 12. The levitation force at 50 K is a little lower than the value of 30 K. The levitation force of 4 tons is obtained with increasing current to 80 A. This result showed that we could obtain the levitation of 4 tons at 50 K of the maximum operation temperature.

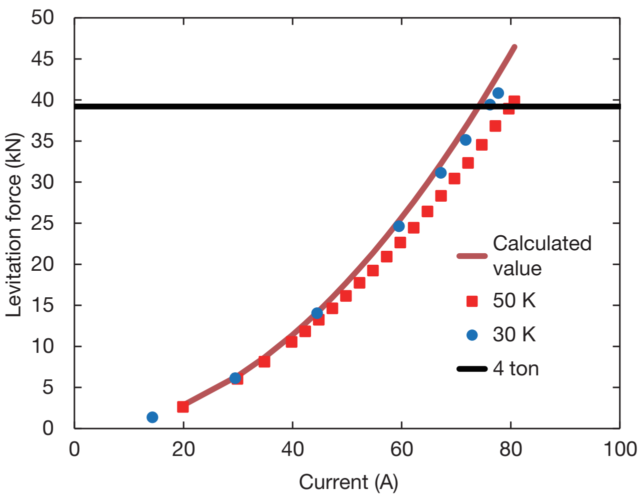

Figure 12 Levitation force dependence on current at 30 K and 50 K.

Figure 13 shows the measured force divided by the calculated force dependence on the current. The value is decreasing with the increasing of current during an excitation and it is deviating from the analysis value. The energizing current is increasing when applying a large magnetic field and a penetration of the flux into the superconducting bulk is increasing for the energizing levitation test, on the other hand, in the analysis case, it assumes that the superconducting bulk repels completely the flux. This is the reason of the deviation between the test result and the analysis. In spite of the current being decreased during demagnetization, the deviation is increased. The result suggests that the penetration flux remains even if the magnetic field decreases.

The magnetic field is detected from a hole element attached to the coil after de-energizing. It presumes that a part of the superconducting bulk is magnetized according to the penetration flux in the bulk. Comparing the value of the 30 K with the one of the 50 K, the value of the 50 K has more deviation from the analysis. The penetration flux of the 50 K is larger than that of the 30 K. The critical current of the superconducting bulk is decreasing with the temperature rising and the penetration flux is increasing. The penetration flux changes the levitation force, the once penetration flux is not removed and is stable in the bulk.

After assembling the FW system, the height of the levitation is not changed for more than 300 hours of the energizing levitation test.

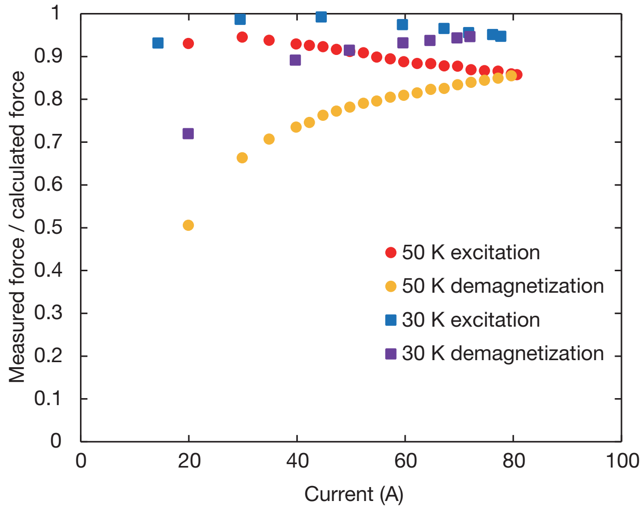

Figure 13 Measured force divided by calculated force dependence on current at 30 K and 50 K.

The levitation force of 4 tons was obtained for the SMB per se and it was confirmed that the levitation was available at 50 K of the maximum operation temperature.

5. THE PERFORMANCE TEST AFTER ASSEMBLING IN THE APPARATUS

The SMB was assembled in the FW energy stored system and the levitation test for the rotor of 4 tons was conducted in April, 2015. After assembling in the FW energy stored system, the temperature of the bulk was not able to be measured and the measured force of the levitation was substituted with a levitation height of the rotor. The relationship between the levitation height and the current is shown Figure 14.

The height remained at 19 mm on de-energization. A touch down bearing was set at a distance of 19 mm between the superconducting coil and the superconducting bulk, and they stayed there during de-energization.

The levitation height did not change at less than 76 A, but the levitation began at more than 76 A, and the height increased with the increasing of the current.

After levitating at 76 A, the height increased 1 mm as current increasing 1 A, and it matched the analysis result that the change of levitation of 1 mm needed the current change of 1 A. The levitation height changed a little on current less than 76 A. The gradually occurred levitation force changed because the strain of 4 tons rotor touched on the touch down bearing was released.

The levitation occurred on energizing of 76 A and we assumed that the superconducting bulk was cooled to less than 30 K. In spite of the shaft connected with the 4 tons rotor and helium gas for cooling the superconducting bulk having a room temperature area in the rotor, the shaft including the superconducting bulk and the helium gas maintained a high heat insulation and had no effect on cooling the superconducting bulk.

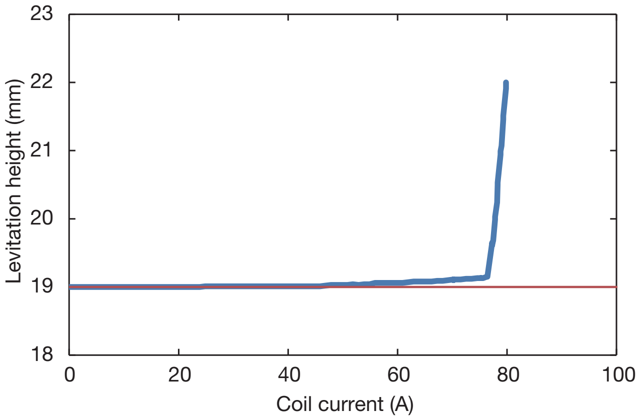

Figure 14 The relationship between the levitation height and the coil current.

In September, 2015, the system was transferred to the mega-solar facility located in Mt. Komekura of Yamanashi for the verification test with non-contact levitation which was conducted for total 1500 hours. The time dependency of the levitation height and the current are shown in Figure 15. The levitation height continued within the control range for more than 300 hours. After the cycle of temperature of cooling and rising for more than 20 times, no deterioration was found with a good the levitation ability, in the case of high rotation of the rotor, there were no problems for either the levitation height or the cooling of the coil.

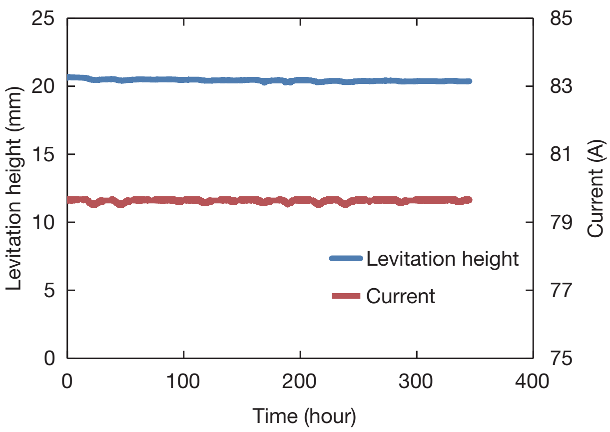

Figure 15 The relationship between the levitation height and time.

The above result suggested that the SMB performed as same as design and analysis, and exhibited a high stability and a high reliability.

6. CONCLUSION

The SMB manufactured this time was specified for the levitation of 4 tons. The analysis suggested further that it was available of levitating of 10 tons and making a larger capacity. The SMB for the verification test was manufactured on the basis of the analysis without a test model, this procedure is suitable to apply to the development of coil in future.

And also, in the verification test, it was able to operate at 50 K which was a high operation temperature as the superconductor appliance with a high magnetic field. The operation at a high temperature helps the refrigerator decrease the power consumption and the thermal stability increases because of a high specific heat. In the case of rising temperature in the abnormal condition, such as the refrigerator stopping, the temperature rise is small because of the large specific heat. It is an advantage for the operation at high temperature to easily handle accidents.

Our target is to apply the high temperature superconductor to the superconductor appliance through the superconducting wire and the superconducting coil generating a strong magnetic field.

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