CONSTRUCTION OF A MODEL MAGNET FOR
SHIELDED PULSED ENERGY STORAGE

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Abstract

The first model magnet system of the shielded pulsed superconductive energy storage was designed and constructed to test the shielding effect. The capacity is 200 kJ. The superconductive coil was designed as a usual dc magnet. The rated current was decided as 1,350 A not to be large heat leak through power leads. The shield coil was divided into 12 blocks which were wound in a solenoid type. These blocks were distributed in optimum distribution not to generate magnetic field on the superconductive coil. This enables the construction of such small scaled shield coil. The system is designed to be able to generate energy of 250 kJ in the duty factor of 0.2 %. The field was measured and well agreed with the calculated one.

Introduction

The superconductive energy storage is one of the most effective methods to feed pulsed energy to loads such as fusion magnets, large accelerators, and power networks, because it has high energy density, high efficiency, and also it can feed big power in a short time to the loads. The ac losses and repeated stresses of the superconductive coil by the pulse operation may degrade the performances of the superconductive energy storage, and make its application to the energy sources difficult. The investigations on the ohmic heating coils have developed fast charging and discharging coils more than 10 T/sec.¹⁾ However many technical problems have to be solved to obtain more stable pulse coils.

The shielded pulsed superconductive energy storage proposed by Moses and Ballou²⁾ has an advantage that any pulse current and magnetic field do not subject the superconductive coil. Any ac losses are not generated in the superconductive coil and also any repeated stresses do not act on it. It has also another merit that it can deliver the energy more than the stored energy in the superconductive coil.

The test should be performed to investigate the shield coil effects, feasibility and other technical problems. The paper describes the design and construction of the first model coil system, and the field measurement of the shield coil.

Shielded Pulsed Energy Storage

The principle circuit of the shielded pulsed energy storage is shown in Fig. 1. The shield coil is connected with the superconductive coil in parallel. They are excited by a converter. The shield coil is distributed around the superconductive coil not to generate any magnetic field on the superconductive coil. It means that the shield coil is linked with the superconductive coil by all of the magnetic flux of the shield coil. The self-inductance of the shield coil L_s equals to the mutual inductance M in case of the same number of turns between two coils.

In the circuit shown in Fig. 1 the superconductive coil current change I_c is given as

$$\dot{I}_c = \frac{1}{L_c - M} (L_s - M) \dot{I}_s + V_s + R_s I_s \quad (1)$$

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Fig. 1 Principle circuit of the shielded pulsed energy storage

When the compensating power supply is controlled as $V_s = -R_s I_s$, $I_c = 0$. Only the dc current flows into the superconductive coil. And no magnetic flux is generated on the superconductive coil. It means that no ac loss is generated in the superconductive coil.

The available energy ΔW from the system is as follows:

$$\Delta W = 2 L_s I_c I_{sm} \quad (2)$$

when the shield coil current is changed from $+I_{sm}$ to $-I_{sm}$. The energy ΔW can be more than the stored energy in the superconductive coil.³⁾

Design of the 200 kJ Model MagnetSuperconductive coil current

We designed the 200 kJ model magnet system for testing the shielding effects. The magnet system is composed of three parts: (1) the superconductive coil generating the dc bias field for the storage, (2) the shield coil generating the pulse field for energy transfer, and (3) the cryostat. The parameters for the superconductive and the shield coils are shown in Table 1.

As for construction of the shield coil, a smaller number of turns makes the construction easy. It means that a larger value of the superconductive coil current is favorable. The larger value of the current, however, increases the heat leak through power leads to the liquid helium temperature. The optimization gave the current as 1,350 A and the number of turns as 528.

Superconductive coil

The desirable cross-section of the superconductive coil is a circle to obtain large mutual inductance between two coils which makes the system to deliver more energy. On the contrary, the easier construction is obtained by the rectangular cross-section. The cross section is square as shown in Fig. 2. The size is 7.4 cm $\times$ 7.4 cm.

The superconductive coil was wound closely with a monolithic superconductive wire which had the cross section of 1.6 mm $\times$ 3.2 mm. The copper-to-superconductor ratio is 3.9. The wire is not specially designed for an ac coil. The rated current and the magnetic field are 1,350 A and 4.0 T, respectively. It is 78 % of the critical value of the short sample wire. The coil is cooled by pool boiling method.

Table 1

Parameters of the 200 kJ model magnet system

Superconductive Coil

Stored Energy	200 kJ
Inductance	0.23 H
Current	1,350 A
Current Density	1.1×10^4 A/cm ²
No. of Turns	528
Max. Field	4.0 T
Main Radius	30 cm
Cross Section	7.4×7.4 cm ²
Cooling Mode	Pool Boiling, 4.2 K

Superconductor

Material	Nb-Ti/Cu
Critical Current	1,770 A at 5 T, 4.2 K
Cu/SC Ratio	3.9
Filament Diameter	32 μ m
No. of Filaments	1,250
Twisted Pitch	25 mm
Cross Section	1.6×3.2 mm ²

Shield Coil

Inductance (Self)	0.082 H
(Mutual)	0.089 H
Max. Current	200 A at 5 % Duty
Max. Current Density	910 A/cm ²
Max. Available Energy	50 kJ at 5 % Duty
No. of Turns	528
Cross Section of Wire	4×5.5 mm ²
Resistivity	0.77 Ω at 300 K
Material	OFHC Copper

Shield coil

As mentioned before, we developed a newly designed winding method for the shield coil. This method enables a relatively large number of turns to wind in the optimized distribution. The shield coil windings were divided into 12 blocks. Each block was wound as a solenoid, and distributed not to generate the field on the superconductive coil. The calculated field distribution is shown as dotted lines in Fig. 5. At the maximum shield coil current, the leakage field on the superconductive coil was 80 G which is only 0.2 % of the dc field by the superconductive coil.

The small leakage field causes the difference between the self-inductance of the shield coil and the mutual inductance. The difference generates the pulse current in the superconductive coil. This is given as follows:

$$\dot{I}_C / \dot{I}_S = (L_S - M) / (L_C - M) \quad (3)$$

In the model coil, the pulse current of 0.7 % to the dc current may be caused by the approximation of the shield coil blocks from the ideal distribution. The properties of the system are hardly affected by such small pulse current.

We used the shield coil wire of OFHC copper of which size was 4 mm $\times$ 5.5 mm. The wire can flow the pulse shield coil current of 200 A in the duty of 5 %. In this case the available energy is 50 kJ in a minimum delivery time of 100 ms. On the other hand, we can derive the energy of 250 kJ in the duty of 0.2 %. It is more than the stored energy in the superconductive coil.

Cryostat

One of the problems of the system is the construction of the cryostat. Especially it is more difficult in such small scale. It should be designed by considering the following items:

- (1) The total thickness of the wall should be as thin as possible because of obtaining the good mutual coupling.
- (2) The heat leak through the magnet supports should be small by using the effective supporting method.
- (3) The good feeding method for the power leads, liquid helium, and measurement leads should be designed.

The cryostat has an octagonal cross section for the thin wall as shown in Fig. 2. This makes the coupling efficiency between the coils better. The nitrogen shield is used with copper pipes.

It is difficult to have enough space for power leads, feeding liquid helium, and other measurement leads because the shield coil is distributed around the superconductive coil. Constructing the shield coil in several blocks can prepare enough space for them as shown in Fig. 2. This method may be applicable to the real system.

The superconductive coil is supported by 24 rods as shown in Fig. 3. The supporting rod is composed of double glass fiber reinforced epoxy pipes on a same axis and stainless steel washers. They have thermal anchors at liquid nitrogen temperature. The heat leak to liquid helium temperature is only 65 mW through one rod though the apparent length is only 30 mm. The yield strength is 1,700 kg for each rod. They can stand sufficiently against the compressive force caused by the misalignment of two coils.

ConstructionSuperconductive coil

As the coil should not be required severely to obtain good cooling and suppress damages by repeated

Fig. 2 Schematic drawing of the 200 kJ model system of the shielded pulsed energy storage.

stresses, the coil was constructed as a usual solenoid. The superconductive coil was wound with the monolithic multi-filament wire on a glass-fiber reinforced epoxy bobbin. Epoxy impregnated glass tapes of 0.25 mm thickness wrapped the superconductive wire so as to cover its surface of 50 %. Spacers, 0.8 mm thick, were used between the winding layers for cooling.

The tension for winding the coil was 20 kg. After winding the coil it was strengthened with epoxy reinforced glass tapes of which thickness was 7 mm. The coil was treated at 150°C for 10 hours in a furnace.

Fig. 3 Supporting rod for the superconductive coil.

Shield coil

The winding the shield coil into the blocks is a sophisticated method in such small scaled model, because of the difficulty of winding in a limited space. However it should be considered to obtain accurate construction and good cooling in this method.

The 12 blocks of the shield coil were wound separately. The coils of the 6 blocks were fixed with epoxy resin, and set on 6 aluminum-alloy bases as shown in Fig. 4. The bases act as the accurate constructing mean and also as the high thermal conductive mean for the shield coil. The other 6 blocks were set by the same method.

The shield coil blocks were molded with high thermal conductivity resin ($\sim 10 \text{ mV/cm}^\circ\text{C}$) with the aluminum bases.

Fig. 4 Assembled blocks of the shield coil on the 12 aluminum bases.

Field Measurement

The field distributions due to the shield coil current of 15 A were measured inside the region surrounded by the blocks of the shield coil. The measurement was done by using a hall probe. At such small current the minimum leakage field is $0.5 \sim 1$ gauss which is same as the earth magnetism. To cancel the effect of the earth magnetism, the measurement was performed on three planes which were on the center axis and separated in angle by each 60° . The errors between the obtained values on three planes were within ± 0.2 gauss.

Fig. 5 Measured and calculated field distributions of the shield coil.

The measured field distributions are shown as solid lines in Fig. 5. The values agreed very well with the calculated ones. The slight differences may be caused by the setting errors of the shield coil blocks.

Losses Due to Pulse Operation

This method has an advantage that no ac loss is generated at the liquid helium temperature, which becomes quite large power losses because of small efficiency of a refrigerator. The ac losses are gene-

Fig. 6 The calculated losses of the shield coil of 21.1 MJ by the operation with a triangular current wave form.

rated only in the shield coil which is operated at the room temperature.

We calculated the losses of the shielded coil system which has the capacity of the available energy of 15 MJ. The capacity is larger than the 30 MJ coil project at LASL.⁴⁾ The stored energy is 21.1 MJ.³⁾ There are, of course, static losses generated at the cryogenic temperature as same as another coil systems. We estimated, however, only the losses due to the pulse operation. The calculated losses are shown in Fig. 6 when the system is operated by triangular current wave forms. The losses are decreased down with the faster operation. The losses by the pulse operation of 1 sec is less than 1 % of the available energy.

Summary

The first model magnet of the shielded coil was constructed with ingenious design that the shield coil was wound in several blocks. The blocks were distributed around the superconductive coil not to generate magnetic field on the superconductive coil. This method enables the shield coil to be constructed easily. Moreover, it provides spaces for feeding liquid helium, current leads, and other equipments.

The magnetic field distributions due to the shield coil current were measured, and agreed well with the calculated ones. There are small leakage fields by winding the shield coil into several blocks. However, it hardly affect adversely the performance of the model system.

The shield coil system is quite useful for pulse loads, especially when it is operated in a short time faster than a few seconds because of no ac loss at the cryogenic temperature. It is applicable not only for pulsed power supplies, but for the stabilization of the electric power utility.

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