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THE FIRST MODEL OF THE SHIELDED PULSED SUPERCONDUCTIVE ENERGY STORAGE

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ABSTRACT

The first model of the shielded pulsed energy storage was designed and constructed to test the effectiveness, the construction problems, and the scaling problems. The stored energy is 200 kJ, and its available energy is designed as 50 kJ at the transfer time less than 50 ms. The shield coil is distributed arround the superconductive coil in a simple form for easy construction. The measurement of the leakage field showed that the simplified distribution of the shield coil was available. The dewar was constructed to have a wall as thin as possible with small heat leak by using GFRP supports. The design value of heat leak agreed well with the measurement. The current of 80 % of the design value was obtained by the first preliminary test with three quenchings.

INTRODUCTION

The pulsed superconductive energy storage has been developed to apply to the power supply of the fusion magnets. Its energy density is remarkably large in comparison with capacitors. It can also feed big power to loads. The fast dischargeable pulsed superconductive coil [1] was tested for the power supply of θ-pinch fusion magnets.

The recent development of Tokamak fusion reactors has requested the pulsed superconductive coil as a ohmic heating coil which can charge and discharge the energy within 1 second. The field change of the coil is more than 10 T/sec. The pulsed superconductive energy storage can be applied to the power supply of the ohmic heating coil.

These pulsed superconductive energy storage, however, has some technical problems to be solved. The first is caused by ac losses generated at liquid helium temperature when the magnets are operated in pulsed mode. It makes the efficiency worse and does the coils unstable. The second is the cyclic stresses caused by the pulse electromagnetic forces. The superconductive coils have not experienced in fatigue by the cyclic stresses. We have also small experience in plastic dewars for suppression of eddy current in dewar walls.

The shielded coil superconductive energy storage proposed by Moses and Ballou [2] took these problems away. The action of the shield coil prevents the superconductive coil to be subjected to any pulse field and current. The fact means that the superconductive coil can be made like a dc magnet.

This paper will report the first model of the shielded pulsed superconductive energy storage which has the stored energy of 200 kJ.

APPLICATION OF THE PULSED SUPERCONDUCTIVE ENERGY STORAGE

As described above, the pulsed superconductive energy storage has been developed as the power supply for the θ-pinch fusion reactor. The obtained know-how for pulse coils has been succeeded to the ohmic heating coil and the energy storage coil for the power supply.

As for the applications to electric power utilities, the stabilization of electric power networks has been developed and is now under construction [3]. This plant is the first practical application of the superconductive energy storage system.

The reactive power compensation is very important to the electric power utilities. The pulsed loads with thyristor converters usually generate pulsed reactive power and then cause voltage oscillation of the networks. The pulsed superconductive energy storage is applicable to compensation of the reactive power and stabilization of the voltage flickers.

PRINCIPLE OF THE SHIELDED SUPERCONDUCTIVE ENERGY STORAGE

The principle of the shielded superconductive energy storage is as follows. The optimum distribution of the shield coil can shield the superconductive coil from magnetic flux due to the shield coil. The magnetic flux of the shield coil can couple completely with the superconductive coil. This means that the self-inductance of the shield coil are equal to the mutual inductance.

When the two coils are connected in parallel to power supplies as shown in Fig. 1. The current change of the superconductive coil is given as the following equation by simple calculation.

$$\dot{I}c = \left\{(Ls - M)\,\dot{I}s + Rs\;Is + Vs\right\}/\;(Lc - M) \qquad (1)$$

where Ic and Is are the superconductive coil and the shield coil currents, and Rs and Vs are the resistance of the shield coil and the voltage of the compensation power supply, respectively. Ic, Ls and M means the self- and mutual inductances of both coils. The current change Ic comes to zero when the conditions Ls = M and Vs = - Rs Is are obtained. The pulse current due to energy transfer does not flow into the superconductive coil but into the shield coil.

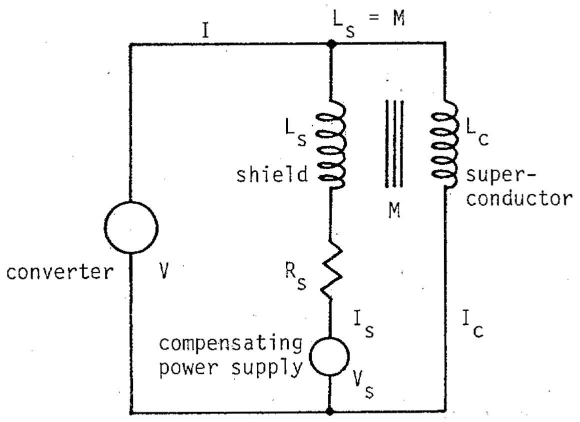

Fig. 1 The circuit of the shielded superconductive energy storage.

In these conditions the superconductive coil is not subjected to any pulse field and current. The superconductive coil has no ac losses and then is very stable.

The schematic field maps are shown in Fig. 2, when the system is charged and discharged. In these figures there is any field change on the superconductive coil.

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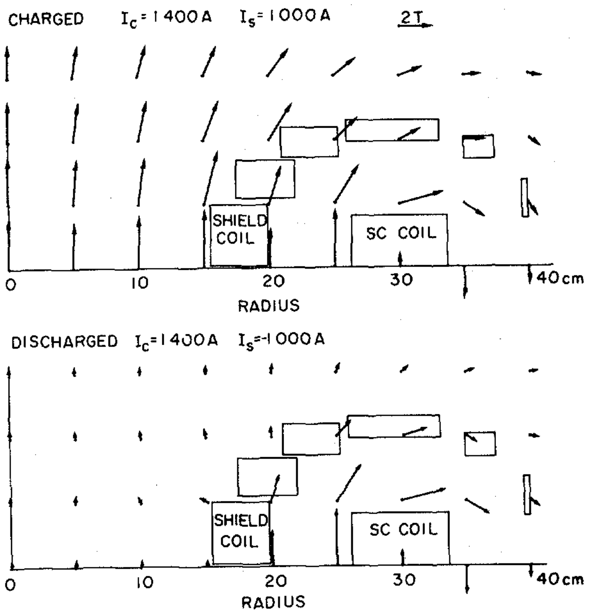

Fig. 2 Field map of the charged and discharged states.

The available energy ΔW of the system is easily derived when the shield coil current changes from + Ism to - Ism. That is

$$W = 2\ Ls\ Ism\ Ic \tag{2}$$

As the self-inductance Ls of the shield coil is usually 80 % of Lc in the actual scale system and the shield coil current Ism can be made as same as Ic, the available energy is more than the stored energy.

THE 200 KJ MODEL COIL

Design Features of the Model Coil System

The precise description of the design was given elsewhere [4].

The purposes of this model are the followings; the verification of the shield coil effect, the study of the production of the shield coil and the dewar in consideration of scaling up, the establishment of the control method, and the study of its applications such as the stabilization of electric power networks.

The superconductive coil can be made as a dc coil with the economical and usual wire. The coil production also should not be given careful considerations to reduce ac losses and to prevent the fatigue due to the repeated electro-magnetic stresses.

The ideal shield coil has continuous angular distribution as shown in Fig. 3. The continuously distributed coil is not easy and may cost much to be constructed. The simplified distribution approximated to the ideal one should be taken even if the system scales up. The simplified distribution, of course, means that the shield coil has not perfect shielding. The calculation of the field distribution due to this type of shield coil showed no problem for the leakage field because it is less than 1 % of the dc field.

To get larger available energy, the shield coil should be wound to the superconductive coil as closely as possible. The thermal insulation, however, is necessary between the shield and the superconductive coil. The dewar is requested to have a thin wall and small heat leak property. In such a small scale the larger heat leak results in lager helium consumption and makes the test difficult. In a practical scale the larger heat leak means the worse efficiency. For these requests glass fiber reinforced epoxy (GFRP) rods have to be employed to support the superconductive coil.

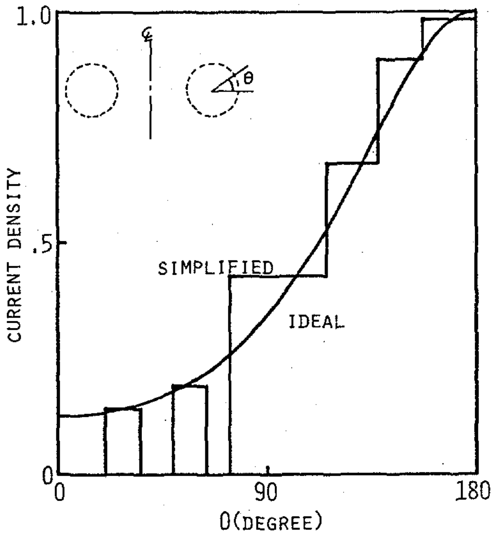

Fig. 3 The ideal and simplified shield coil distributions.

Parameters of the Coil System

The parameters of the 200 kJ model coil are shown in Table 1. The current of the superconductive coil was decided from the point of view of the heat leak to liquid helium temperature through power leads. The rated current was designed as 1,350 A in consideration of the heat leak. A monolithic superconductive wire was adopted, and its Cu/SC ratio is 3.9. The critical current of the wire is 1,770 A at 4.2 K and 5T for the short sample.

The shield coil has the same number of turns as the superconductive coil to obtain the condition of $Ls = M$. There is a little difference between the self- and the mutual inductances caused by the deviation of the shield coil distribution from the ideal one. The deviation will generate the pulse field and current in the superconductive coil when the system is operated in pulse mode. These are, however, less than 1 % in calculation. Such small deviation may not affect the stability of the superconductive coil.

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
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

Construction

The superconductive coil was wound closely wire to wire with the monolithic wire on a GFRP bobbin. The surface of the wire was covered by 50 % with epoxy impregnated glass tape of 0.25 mm thick. Spacers of 0.8 mm thick were used between the layers for cooling. The winding tension was 20 kg. The coil was strengthened with epoxy reinforced glass tapes of which thickness was 7 mm after winding. The coil was treated at 150 °C for 10 hours.

The superconductive coil was supported with 24 GFRP rods as shown in Fig. 4. It can stand the compressive force of 1.7 tons. The calculated heat leak is only 1.6 W in total.

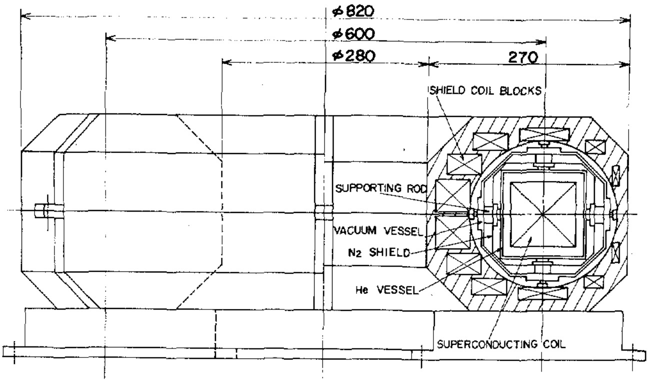

Fig. 4 The drawing of the model coil.

The shield coil blocks were distributed arround the superconductive coil in accordance with the simplified distribution as shown in Fig. 4. Each block was wound seperately by a winding machine and assembled on aluminum bases. The bases are effective to get high accuracy for assembling them and high thermal conductivity for cooling. After assembling the blocks were molded with epoxy resin with high thermal conductivity.

Control Circuit for Energy Transfer

The deviation between the self- and the mutual inductances, Ls and M, results in flowing the pulse current into the superconductive coil. The calculation shows that the pulse current of 0.7 % to dc current Ic flows into the coil. The current can be compensated to zero by controlling the compensation power supply. The control block diagram is shown in Fig. 5. The feedback control by the signal of Ic makes complete compensation of the pulse current in the superconductive coil. This control system can make the easier construction of the shield coil, that is, the simplified distribution.

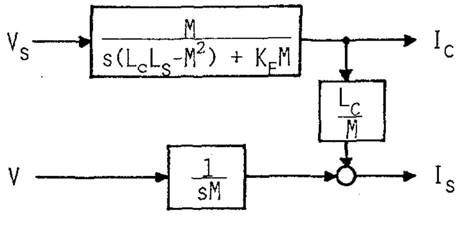

Fig. 5 The block diagram of the control system including the coils.

PRELIMINARY TEST OF THE MODEL COIL

Field Measurement

The leakage field due to the simplified shield coil distribution was measured inside area surrounded by the shield coil with a Hall probe. The results are shown in Fig. 6. The values show the fraction of the leakage field to the field of the shield coil on the central axis. Almost of the superconductive coil winding is included in the area less than 3 %. The value of 3 % corresponds to 0.2 % of the dc field when the rated current flows in the shield coil. The result shows that there is almost no pulse field which causes ac losses when the energy transfer is performed.

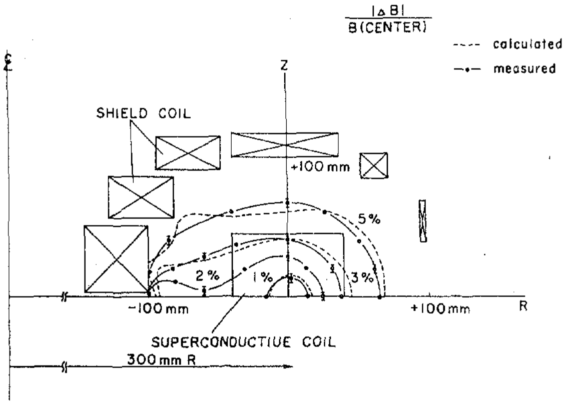

Fig. 6 Measured leakage field due to the shield coil.

The leakage field will show the difference between the inductances, Ls and M, which are calculated in Table 1. This will also flow the pulse current of 0.7 % of the dc current into the superconductive coil. As mentioned above, the current can be compensated to zero by the sophisticated control system.

The field measurement shows the good agreement with the calculation.

Preliminary Excitation Test

The preliminary excitation test was performed to obtain the cooling and the excitation characteristics of the superconductive coil. The system in test is shown in Fig. 7. The upper part of the shield coil is removed to show the dewar.

It took 3 hours to cool down the superconductive coil and the thermal shield to 80 K. As the thermal shield is cooled with the pipes contacted on it, the cooling to 80 K is not fast even though the system is small. After the coil and the thermal shield were cooled to 80 K, liquid helium was poured into a reservoir. The coil got into superconductive state about 2 hours after that.

Liquid helium of 45 ℓ was consumed to cool down the coil from 80 K to 4.2 K. The heat leak to 4.2 K was measured by the evaporation method. It was 5.1 W including power leads and the helium reservoir. The heat leak to the dewar was in good agreement with the calculation in consideration of the heat leak through the power leads and the reservoir.

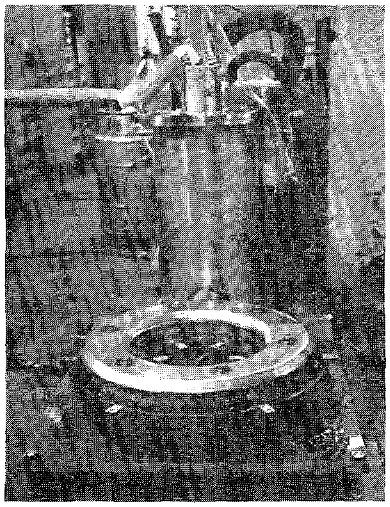

Fig. 7 The model coil in test.

The preliminary test was performed for the excitation of only the superconductive coil. The first quenching of the coil was at the current of 934 A. In this test there were three quenchings up to the current of 1,047 A which was 80 % of the rated current.

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