Development of UPS-SMES as a Protection From Momentary Voltage Drop

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Abstract—We have been developing the UPS-SMES as a protection from momentary voltage drop and power failure. The superconducting system is suitable as electric power storage for large energy extraction in a short time. The most important feature of superconducting coil system for the UPS-SMES is easy handling and maintenance-free operation. We have selected Low Temperature Superconducting (LTS) coils instead of High Temperature Superconducting (HTS) coils from the viewpoint of cost and performance. However, it is difficult for the conventional LTS coils to fulfill maintenance-free operation since the cooling methods are either pool boiling with liquid helium or forced flow of supercritical helium. Thus, a conduction cooled LTS pulse coil has been designed as a key component of the UPS-SMES. The development program of 1 MW, 1 sec UPS-SMES is explained.

Index Terms—Conduction cooled, momentary voltage drop, power failure, UPS SMES.

I. INTRODUCTION

IN INFORMATION machines and equipment, such as a computer, the uninterruptible power supply (UPS) is becoming indispensable for data protection. On the other hand, in industrial fabrication facilities such as a semiconductor chip production equipment or large-sized experimental facilities for big science such as a nuclear fusion experimental device, there is no effective protection for the momentary voltage drop and power failure due to their large electrical capacities. This leads to the serious damage for a yield fall of products or a discontinuation of important experiment. In general, most of troubles for the commercial electric power system are less than 1 second. Therefore, the UPS with a large capacity of MW and short time duration of 1 second is very useful not only for the above-mentioned applications but also for broad fields. We have been developing the UPS-SMES as a protection from momentary voltage drop and power failure. Five-year project to develop UPS-SMES is being started from 2002 fiscal year

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as one of the research promotion program of the New Energy and industrial technology Development Organization (NEDO). As the first step, we have been developing a 100 kJ class UPS-SMES in order to do a principle actual proof. Then we are planning to develop a 1 MW, 1 sec UPS-SMES. The design and development of the 100 kJ coil and the electrical circuits for the UPS-SMES are reported in the related papers [1] and [2], respectively. The design concept of a conduction cooled LTS pulse coil for 1 MW, 1 sec UPS-SMES are described in this paper.

II. CONCEPT OF UPS-SMES

A. Basic Idea of UPS-SMES

Fig. 1 shows a basic block diagram for UPS-SMES, which consists of an AC switch, an AC/DC converter, a superconducting (SC) coil system, a SMES control system and a compensable electric load. The AC switch disconnects the compensable electric load from the electric power system when a momentary voltage drop or a power failure occurs. The AC/DC converter discharges the SC coil system to compensate an electric power of the compensable electric load when the AC switch opens. The SC coil system is used as electric power storage which is suitable for large energy extraction in a short time. The SMES control system detects a momentary voltage drop and controls the AC switch and the AC/DC converter.

B. Selection of Superconducting Coil and Cooling System

The comparison of superconductor for a SC coil system is listed in Table I [3]. Because NbTi is an alloy, the mechanical properties are excellent compared with Nb_3Sn of a compound, or HTS of ceramics. Moreover, NbTi can obtain high critical current density by deposit processing. They are suitable for manufacturing a long superconducting wire industrially. A NbTi coil has advantages of low cost, easy handling, low AC loss and high commercial productivity, which make up for disadvantages of low critical temperature and a large coil size caused by the low thermal margin in conduction cooled operation. A Nb_3Sn coil could improve the demerit of a NbTi coil. However, it has the demerit of high cost and difficult handling due to the heat treatment of making Nb_3Sn compound. A HTS coil is attractive for the future use; however, it can not be selected now due to the low cost performance. We have selected a NbTi coil as an adequate solution considering the practical use of UPS-SMES.
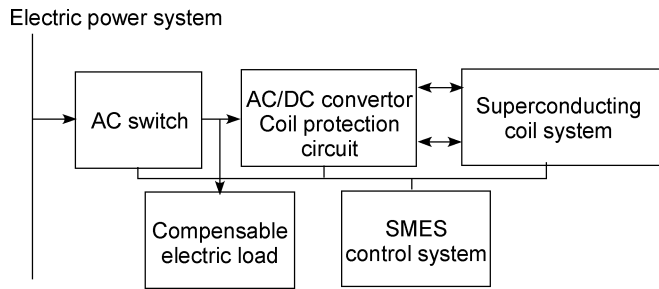
Fig. 1. Block diagram for UPS-SMES.

TABLE I
COMPARISON OF SUPERCONDUCTOR FOR PULSE COIL

Superconductor	LTS		HTS
	NbTi	Nb₃Sn	
Cost	A	B	C
Handling	A	B	B
AC loss	A	B+	C
Commercial productivity	A	A-	C
Critical temperature	C (9.1 K)	B (18.3 K)	A (Bi2223:110 K)
Coil size	C	A	B
Total	A	A-	B-

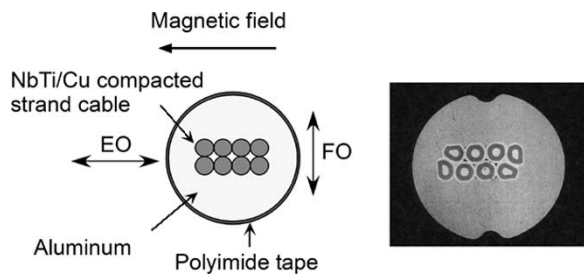A: excellent, B: average, C: inferior

Fig. 2. Cross sectional view and photograph of SC conductor. AC loss is the minimum when the changing magnetic field is applied to EO orientation.

The SC coils for UPS-SMES are required to do pulse operation. The LTS pulse coils are usually cooled with pool boiling of the liquid helium (LHe) or forced flow of the supercritical helium (SHe). The pool boiling of LHe is widely used from the large scale application of superconducting magnet to the small experimental device. However, the handling of LHe needs technical knowledge and the unsuitable handling becomes a cause of failure. Furthermore, the LHe pool-boiling system becomes dangerous when the liquid helium evaporated rapidly due to a certain accident such as vacuum failure of cryostat. The forced flow of SHe is used for the large scale system such as a fusion experimental apparatus. Since it needs a special refrigerator with a circulation system of SHe, it is not suitable for UPS-SMES which requires easy handling. The conduction cooling has become popular as a cooling method for the cryocooler cooled LTS magnet. However, the application of the cryocooler cooled LTS magnet has been restricted only for DC use because of temperature rise accompanying AC loss. The merits and demerits of each cooling system are summarized in Table II. The most important features of SC coil system for

TABLE II
COMPARISON OF COOLING SYSTEM OF SC PULSE COILS

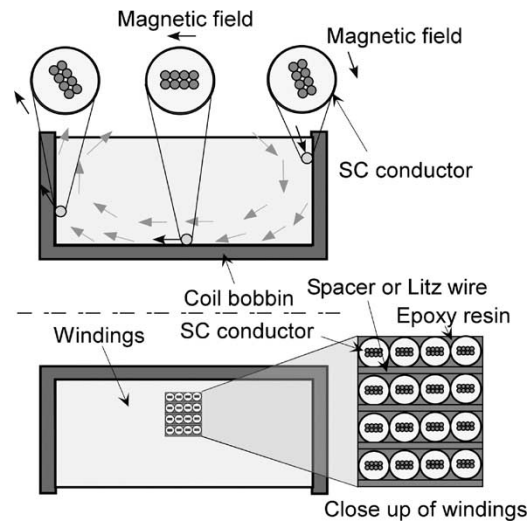| Cooling system	Conduction cooling	Pool-boiling of LHe	Forced-flow cooling of SHe
Easy maintenance	A	B	C
Easy operation	A	B	C
Reliability	A	B	B
Safety	A	C	B
Cost of cryogenic system	A	A	C
Cooling efficiency	C	B	A
Coil size	C	A	B
Coil stability	C	A	A
Total	A	B+	B-

A: excellent, B: average, C: inferior

Fig. 3. Twist winding of conduction cooled pulse coil.

the UPS-SMES are easy handling, maintenance-free, high reliability and safe. We have selected the conduction cooling system as a most reliable and safety cooling scheme for the UPS-SMES which will be installed in a closed room.

C. Development of the Superconducting Conductor

The reduction of AC loss and high stability are required simultaneously for the SC conductor of the UPS-SMES. We have developed the SC conductor with the cross section shown in Fig. 2 and the specification listed in Table III.

A NbTi/Cu compacted strand cable, which is extruded with an ordinal aluminum (Al-1197), is designed to minimize the coupling loss when the changing magnetic field is applied to the edge-on orientation of the compacted strand cable (EO orientation). The AC loss of the conductor was measured with a short sample. The coupling time constant of EO orientation $n\tau_{EO}$ is 10 msec, although the coupling time constant of the face-on orientation of the compacted cable (FO orientation) $n\tau_{FO}$ is 82 msec [4]. Aluminum is adapted not for a stabilizer but for a supporting structure of the twist winding to arrange the face side of the compacted cable parallel to the magnetic field orientation in the coil as shown in Fig. 3. The aluminum is also necessary as a heat sink to reduce temperature rise during pulse operation.

TABLE III
SPECIFICATIONS OF A SUPERCONDUCTING CONDUCTOR

Conductor type	Aluminum coated NbTi/Cu compacted strand cable
Conductor diameter	5.8 mm
Cross section shape	Round with two grooves
Operational current	1000 A
Critical current	3740 A @ 5 T, 4.2 K
Insulation	25 μm thick × 15 mm wide Half wrap winding of Polyimide tape
Outer diameter with insulation	5.9 mm
Tensile strength	96 MPa
0.2 % Yield strength	49 Mpa
Weight	94.3 kg/km
Coupling time constant of AC loss	$n\tau_{FO}$: 82 msec for face-on orientation $n\tau_{EO}$: 10 msec for edge-on orientation
Compacted strand cable	
Number of strands	8
Strand diameter	0.823 mm
Dimension	1.55 × 3.36 mm
Aluminum coating	
Material	Al-1197
RRR	9.85

III. DESIGN CONCEPT OF A CONDUCTION COOLED PULSE COIL

A. Optimum Magnetic Field

Fig. 4 shows a typical operational status of the 1 MJ SC coil for the UPS-SMES during the compensation of 1 sec power failure. The coil current reduces as $1/\sqrt{2}$ from 1000 A to 707 A in 1 sec, while the stored energy reduces as 1/2 from 1 MJ to 0.5 MJ per one coil. After the quick discharge of 1 sec, the coil is charged up to the nominal current of 1000 A with slow ramp speed.

The fixed parameter of the SC coil for the UPS-SMES is the stored energy. We can select freely its magnetic field shape and strength. However, there is a limit coming from temperature rise of the SC conductor due to AC loss during pulse operation. Fig. 5 shows the allowable magnetic field of the conductor under 1 sec pulse operation.

The critical current of the conductor I_c under the magnetic field B and the temperature T is expressed empirically with the following equations [5]:

$$I_c(B,T) = \alpha(T)B^{\gamma-1}\left(1 - \frac{B}{B_{c2}(T)}\right)^{\delta} \quad (1)$$

$$\alpha(T) = \alpha(T_0)\left(\frac{T_{c0} - T}{T_{c0} - T_0}\right) \quad (2)$$

$$B_{c2}(T) = B_{c2}(0)\left[1 - \left(\frac{T}{T_{c0}}\right)^2\right] \quad (3)$$

where $B_{c2}(T)$ is the upper critical magnetic flux density at temperature T, $\alpha(T)$ is a function corresponding to the temperature dependence of the critical current, T_{c0} is the critical temperature at 0 field, γ and δ are constant parameters for the magnetic field dependence of the critical current. For a NbTi conductor, it is usually obtained that $\gamma = 0.5$, $\delta = 1$, $T_{c0} = 9.08$ K and $B_{c2}(0) = 15$ T. $\alpha(T_0)$ is fixed as 14,580 from the measured data of the critical current at $T_0 = 4.2$ K.

Then the current sharing temperature at the beginning of the discharge process $T_{s\_biginning}$, which indicates the upper limit
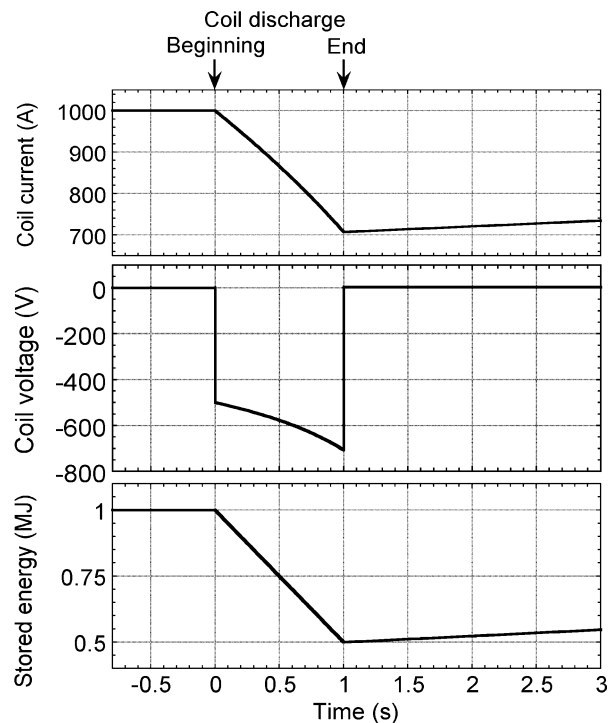

Fig. 4. Operational status of 1 MJ pulse coil during the compensation.
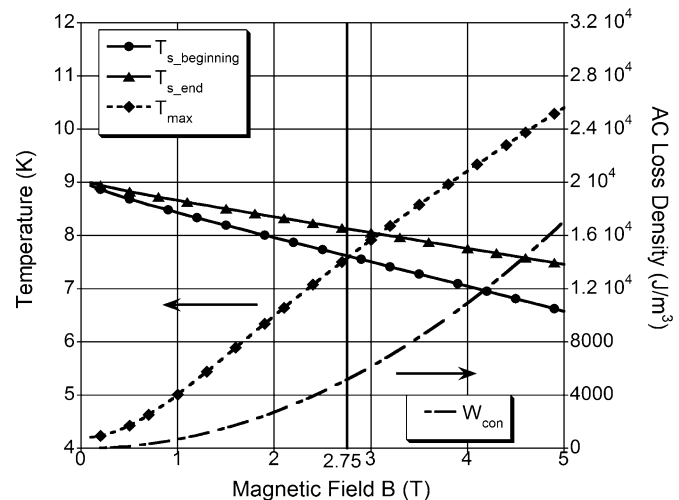

Fig. 5. Allowable magnetic field for the conductor under 1 sec pulse operation. Where $T_{s\_beginning}$ is the current sharing temperature at 1000 A (beginning of the discharge process), T_{s_end} is the current sharing temperature at 707 A (end of the discharge process), as a function of the magnetic field. W_{con} is the AC loss density of the conductor after 1 sec pulse operation. T_{max} is the maximum temperature of the conductor due to the AC loss assuming adiabatic condition.

of the coil operating temperature, is calculated as the temperature when $I_c(B, T_{s\_beginning}) = 1000$ A using the software Mathcad. The current sharing temperature at the end of the discharge T_{s_end} is also calculated as the temperature when

$$I_c\left(\frac{B}{\sqrt{2}}, T_{s\_end}\right) = 707 \text{ A}.$$

Assuming that the magnetic field B is applied to the edge-on (EO) orientation of the compacted strand cable inside the conductor (the low AC loss orientation), the coupling loss density
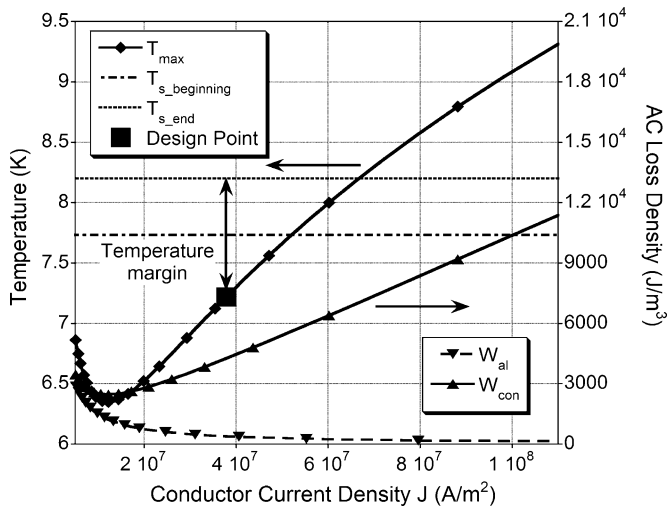
Fig. 6. Temperature margin vs. conductor current density. Wcon is the total AC loss density and Wal is the eddy current loss at the aluminum during 1 sec pulse operation from the magnetic field of 2.5 T assuming adiabatic condition. Tmax, Ts_biginning, Ts_end are the same meanings as in Fig. 5.

of the conductor $W_{con}(B)$ after 1 sec pulse operation is calculated as a function of the magnetic field as follows:

$$W_{con}(B) = \frac{n\tau_{EO}}{\mu_0} \left[B \left(1 - \frac{1}{\sqrt{2}} \right) \right]^2 \qquad (4)$$

where $n\tau_{EO}$ is the coupling time constant when the changing magnetic field is applied to the EO orientation, μ_0 is the permeability of vacuum. Neglecting the hysteresis loss, which is smaller than the coupling loss in this operating condition, the maximum temperature of the conductor T_{max} due to the AC loss is calculated assuming adiabatic condition.

From Fig. 5, the magnetic field is restricted under 2.75 T in order to satisfy the condition that the maximum temperature of the conductor T_{max} is less than the current sharing temperatures ($T_{s\_beginning}$ and T_{s_end}). We decide the maximum magnetic field in the coil as 2.5 T considering a temperature margin.

B. Optimum Current Density

The current density of the conductor is 37.8 A/mm^2. It is relatively low value even through the maximum magnetic field is restricted to 2.5 T. However, the low current density is necessary to satisfy the adequate temperature margin.

Fig. 6 shows the temperature margin vs. conductor current density. The conductor current density is changed with the aluminum diameter under the condition that the cross section of NbTi/Cu compacted strand cable is fixed. The AC loss of the conductor W_{con} is calculated as the sum of the coupling current loss of the compacted strand cable and the eddy current loss in aluminum during 1 sec pulse operation from the beginning magnetic field of 2.5 T. Then the maximum temperature of the conductor T_{max} due to the AC loss is calculated assuming adiabatic condition. $T_{s\_beginning}$ and T_{s_end} show the current sharing temperatures at the beginning of discharge (1000 A, 2.5 T) and the end of the discharge (707 A, 1.77 T), respectively.

The maximum temperature with the current density of 37.8 A/mm^2 is 7.2 K after 1 sec pulse operation. The current
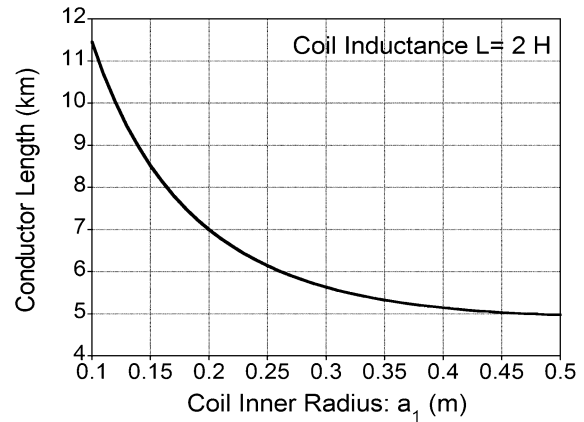

Fig. 7. Required conductor length vs. coil inner radius under the condition of the constant coil inductance of 2 H.
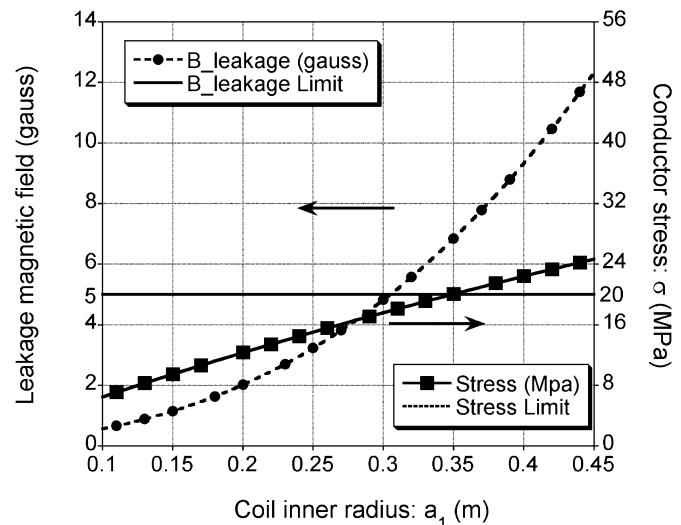

Fig. 8. Leakage magnetic field and conductor stress vs. coil inner radius.

sharing temperature at 707 A (end of discharge) is 8.2 K. Therefore the temperature margin is 1.0 K.

In Fig. 6, W_{al} shows the eddy current loss of aluminum, which becomes larger at low current density region because of the increase in cross-section area of the aluminum part. However, the eddy current loss of the aluminum at design current density is negligible comparing to the coupling current loss of the compacted strand cable because of low residual resistivity ratio ($RRR = 9.85$) of the aluminum. In this SC conductor, the aluminum part is very effective to increase the temperature margin without increasing the AC loss.

C. Leakage Magnetic Field and Mechanical Strength

The inductance and magnetic stored energy of the coil become larger as increasing the coil inner radius under the fixed condition of conductor length. It means that the large inner diameter and short axial length coil is better to reduce the length of conductor under the fixed inductance. Fig. 7 shows a calculated result of the conductor length which is required to wind a coil with the constant inductance of 2 H as a function of the coil inner radius. However, the coil inner radius is restricted from the limits of leakage magnetic field and conductor stress.

TABLE IV
SPECIFICATIONS OF A 1 MJ PULSE COIL

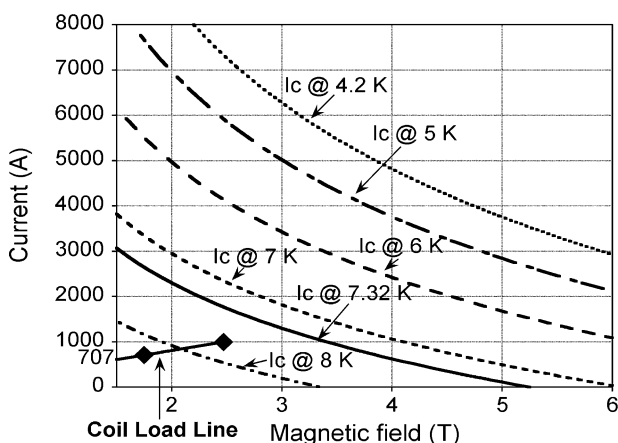| Cooling method	Conduction cooling with a cryocooler
Dimension of the windings	
Inner radius: a1	0.300 m
Outer radius: a2	0.402 m
Length: 2L	1.098 m
Number of turns per 1 layer	183
Number of layers	14
Length of conductor	5.65 km
Inductance	2.00 H
Maximum magnetic field in coil	2.48 T
Magnetic stored energy	1 MJ
Start operating current	1000 A
Stop current after 1 sec discharge	707 A
Discharge energy per one coil	500 kJ
Initial operating temperature	4.2 K

TABLE V
COMPARISON BETWEEN TWIST WINDING COIL AND FLAT WINDING COIL

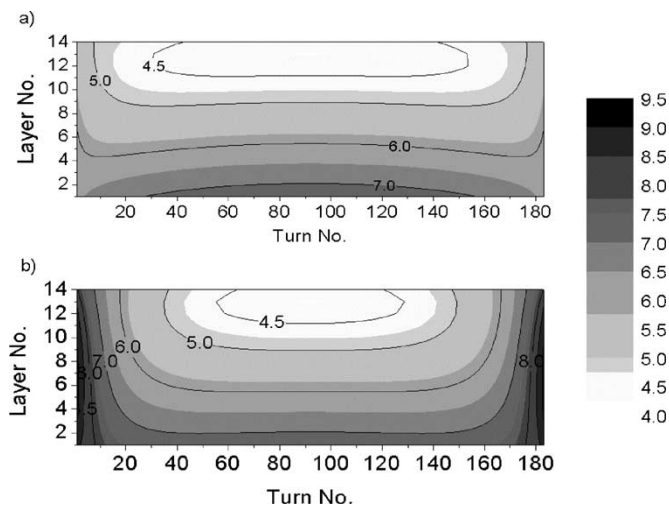| Winding method	Twist winding coil	Flat winding coil
Maximum temperature after 1 sec discharge	7.32 K	9.19 K
Position of max. temp.	1 layer, 92 turn	6 layer, 1 turn
Magnetic field at max. temp. point after 1 sec discharge (before discharge)	1.76 T (2.49 T)	1.12 T (1.59 T)
Coil current after 1 sec discharge (before discharge)	707 A (1000 A)	←
Current sharing temp:Ts after 1 sec discharge (707 A)	8.21 K @ 1.76 T	8.48 K @ 1.12 T
Critical current at max. temp. point	2643 A @ 7.32 K	quench (over Ts)
Maximum AC loss density	4.51 kJ/m^3	10.81 kJ/m^3
Total AC loss	204 J	349 J
Coupling loss	174 J	319 J
Hysteresis loss	30 J	←

Fig. 9. Load line of the optimized 1 MJ pulse coil.

Fig. 10. Temperature rises of the twist winding coil and the flat winding. a) Tmax of 1MJ twist winding coil; b) Tmax of 1MJ flat winding coil.

Fig. 8 shows the leakage magnetic field and the conductor stress as a function of the coil inner radius. The leakage magnetic field is calculated at 5 m distance from the center with two coils configuration for 1 MJ, 1 sec UPS-SMES, in which two coils are arranged in parallel and magnetized in opposite direction. The layer number of the coil windings is fixed to 14 and the length of coil is varied under the condition of the constant inductance of 2 H. The coil inner radius should be less than 0.3 m due to the limit of the leakage magnetic field of 5 gauss at 5 m apart from the center. The coil inner radius is also restricted less than 0.35 m from the stress limit of the conductor <20 MPa.

IV. DESIGN OF 1 MJ PULSE COIL SYSTEM

The optimized design specifications of the 1 MJ pulse coil are listed in Table IV. Two 1 MJ coils are necessary for a 1 MJ, 1 sec UPS-SMES, in which two coils are arranged in parallel and magnetized in opposite direction. Fig. 9 shows the load line of the coil. The coil has large stability margin at 4.2 K operation as compared with the critical current of 4.2 K. However, the margin reduces according to the temperature rise and becomes adequate when the coil temperature rises to 7.32 K after 1 sec discharge operation as calculated in Table V and Fig. 10(a).

The comparison of the twist winding coil and flat winding coil are listed in Table V. The contour maps of temperature rise after 1 sec discharge are shown in Fig. 10. The twist winding coil is wound controlling the twist angle of the conductor so as to arrange the conductor EO orientation and the magnetic field orientation in the coil. The flat winding coil is wound without twisting of the conductor.

The AC loss of each turn in the coil windings is calculated as the sum of the coupling loss and the hysteresis loss of the conductor. The hysteresis loss is took into account because it can not be negligible compared with the coupling loss at the low magnetic field and the high critical current region in the coil. Then the distribution of the temperature rises in the coil due to the AC loss is calculated assuming adiabatic condition.

The maximum temperature in the twist winding coil after 1 sec discharge is 7.32 K, whereas the current sharing temperature is 8.21 K. Therefore, the twist winding coil can be operated within the temperature margin of 0.9 K. However, the maximum temperature of the flat winding coil after 1 sec discharge is 9.19 K, which exceeds the current sharing temperature of 8.48 K, and the coil quenches.

V. Summary

We have been developing 1 MW, 1 sec UPS-SMES as the five years project from 2002. The conduction cooled LTS pulse coil has been designed as a key component of this UPS-SMES. The design optimization of 1 MJ conduction cooled pulse coil has been done as a base on the measured AC loss data of the manufactured SC conductor. The new twist winding method is adapted to the coil, which can reduce the AC loss and enables stable operation of the coil within the temperature margin. We have developed the special winding machine for the twist winding and have been constructing 100 kJ coil to do a principle actual proof. We are planning to construct a 1 MW, 1 sec UPS-SMES and to perform the long-term field test in NIFS as the final stage of the project.

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