Prototype Development of a Conduction-Cooled LTS Pulse Coil for UPS-SMES

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***Abstract*—We are planning to develop a 1 MW, 1 sec UPS-SMES for a protection from a momentary voltage drop and an instant power failure. As the first step, we have been developing a 100 kJ class prototype UPS-SMES, using a low temperature superconducting coil because of its better cost and performance over the high temperature superconducting coil. However, the difficulty to utilize a pool-boiling LTS pulse coil is the reliability of operation. To solve this problem, a conduction-cooled LTS pulse coil has been designed and fabricated as a key component of the UPS-SMES. The reduction of AC loss and high stability are required for the SC conductor for the conduction-cooled coil because of a limited cooling capacity. The SC conductor of a NbTi/Cu compacted strand cable extruded with an aluminum is designed to have the anisotropic AC loss properties to minimize the coupling loss under the specified orientation of the time varying magnetic field. The coil was wound with a new twist-winding method in which the variation of twist angle of the conductor was controlled with the winding machine designed specifically for this purpose. The fabrication technique and performance of a conduction-cooled prototype LTS pulse coil are described.**

***Index Terms*—Conduction cooled, momentary voltage drop, superconducting pulse coil, UPS-SMES.**

I. INTRODUCTION

A momentary voltage drop and an instant power failure result in serious damage to production lines of an industrial plant. An uninterruptible power supply (UPS) with short time duration but large electric power capacity has been required as a suitable protection from those accidents. A Low Temperature Superconducting (LTS) pulse coil has excellent characteristics in the short-time energy extraction, which is adequate for a short-time UPS. Thus, we determined to utilize conductively cooled LTS pulse coil because of their higher reliability and easier operation than conventional cooling schemes such as a pool boiling or forced-cooling. Five-year project to develop a UPS-SMES with a capacity of 1 MW and a short time duration of 1 second started in the 2002 fiscal year as one of the research promotion program of the New Energy and industrial technology Development Organization (NEDO) [1]. To confirm the feasibility of SMES with the LTS pulse coil, we have fabricated a prototype coil with stored energy of 100 kJ. The paper describes a development of pulse coils with a new winding technique.

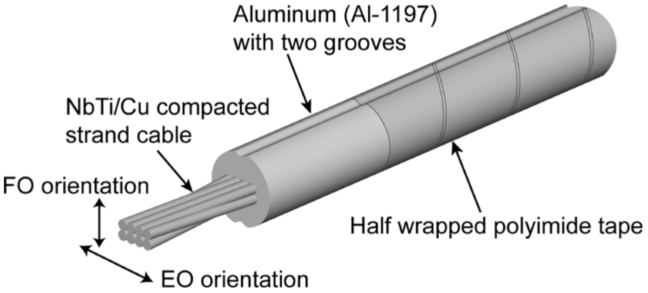

Fig. 1. Superconducting conductor for the LTS pulse coil.

II. DESIGN OF A CONDUCTION-COOLED LTS PULSE COIL

A. Low AC Loss and High Stability SC Conductor

A low AC loss and a high stability are required for the superconducting (SC) conductor of the conduction-cooled LTS pulse coil. The SC conductor of a NbTi/Cu compacted strand cable extruded with aluminum has been developed, whose configuration is shown in Fig. 1 and the parameters are listed in Table I. A NbTi conductor has advantages over $\mathrm{Nb_3Sn}$ and/or HTS conductors because of low cost, easy handling and high commercial productivity

The conductor has the anisotropic coupling loss properties depending on the orientation of the time varying magnetic field. The coupling loss becomes the minimum when the time varying magnetic field is applied on the edge-on (EO) orientation to the compacted strand cable in the conductor. Therefore, the AC loss of the coil can be minimized as twisting the conductor during the winding process so that the EO orientation of the conductor coincides with the orientation of the magnetic field in the coil. An ordinal aluminum (Al-11 197) with a small residual resistivity ratio of 9.85, which is extruded with a NbTi/Cu compacted strand cable, is adapted not for a stabilizer but for a supporting guide of the twist winding to minimize the AC loss. The aluminum is also important as a heat sink to suppress temperature rise during the pulse operation of the conduction-cooled coil. The conductor has two grooves on the round shape cross section as shown in Fig. 1 to detect the angle of the compacted strand cable inside the conductor.

The estimated inter-strand contact resistance in the compacted strand cable of the conductor is very small about

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TABLE I
SPECIFICATIONS OF THE SC 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: nτ	82 msec for face-on (FO) orientation 10 msec for edge-on (EO) 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

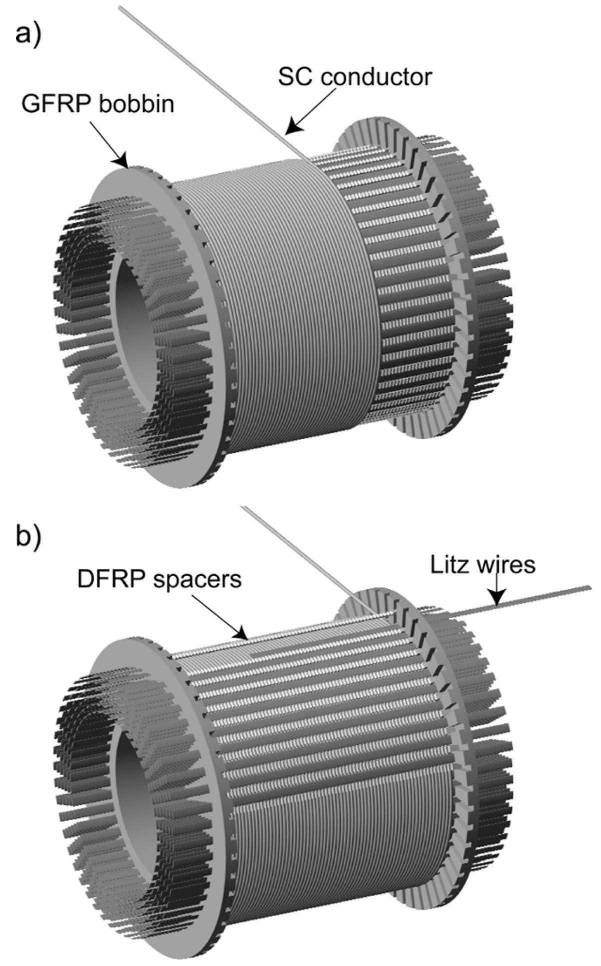

Fig. 2. Winding procedure of the prototype LTS pulse coil, a) winding each layer, b) setting DFRP spacers and inserting Litz wires after the winding of each layer.

$10^{-12}\ \Omega\mathrm{m}^2$, which ensures good current redistribution characteristics and a high stability of the conductor [2].

TABLE II
SPECIFICATIONS OF THE PROTOTYPE LTS PULSE COIL

Cooling method	Conduction cooling with Litz wires
Coil shape	Solenoid
Winding method	Twist winding to minimize AC loss
Dimension of the coil windings	
Inner diameter: 2a1	0.305 m
Outer diameter: 2a2	0.509 m
Length: 2L	0.402 m
Number of turns per 1 layer	67
Number of layers	14
Total turn number	938
Total length of conductor	1.20 km
Coil inductance	0.20 H
Maximum magnetic field	2.2 T
Magnetic stored energy	100 kJ
Start operating current	1000 A
Stop current after 1 sec discharge	707 A
Maximum discharge energy	50 kJ
Litz wies for conduction cooling	Braided wires of insulated copper strands
Sum of copper cross-section	4,774 × 2 = 9,548 mm^2
Total coil weight	400 kg
Superconducting conductor	113 kg
GFRP winding bobbin	70 kg
DFRP spacers	40 kg
Litz wires	115 kg
Epoxy resin	39 kg
Others	23 kg

B. *Configuration of Prototype Conduction-Cooled Pulse Coil*

The winding procedure of the prototype conduction-cooled LTS pulse coil is shown in Fig. 2 and its parameters are listed in Table II. The coil shape is a single solenoid of 67 turns × 14 layers wound on the GFRP bobbin. The Dyneema FRP (DFRP) spacers and the Litz wires (braided wires of insulated copper strands) are inserted in each layer as shown in Fig. 2(b). The DFRP spacers with a thickness of 10 mm and a length of 428 mm have been machined with the semi-circle grooves so that the round conductor can be settled at the exact winding position. The transition of the windings from a layer to the next layer can be done easily by changing the position of the semi-circle grooves at both ends of the DFRP spacers according to their circumferential settled position.

The DFRP spacers have a good thermal conductivity along with Dyneema filaments, which enhance the heat transfer from layer to layer in the windings. On the other hand, the Litz wires increase the heat transfer from turn to turn in the windings and enable conduction cooling of the coil by attaching the end of the Litz wires directly to the cold heads of the cryocoolers.

III. CONSTRUCTION OF THE PROTOTYPE CONDUCTION-COOLED PULSE COIL

A. *Development of the New Winding Technique*

A difficult point to fabricate a conduction-cooled pulse coil is how to twist the SC conductor according to the orientation of magnetic field in the winding process. It is also necessary to establish a fabrication technique which is simple and suitable for mass production of UPS-SMES coils. Therefore, we have developed an automatic winding machine which can control a twisting angle of the conductor according to the winding position as shown in Fig. 3. The twisted angle of the conductor

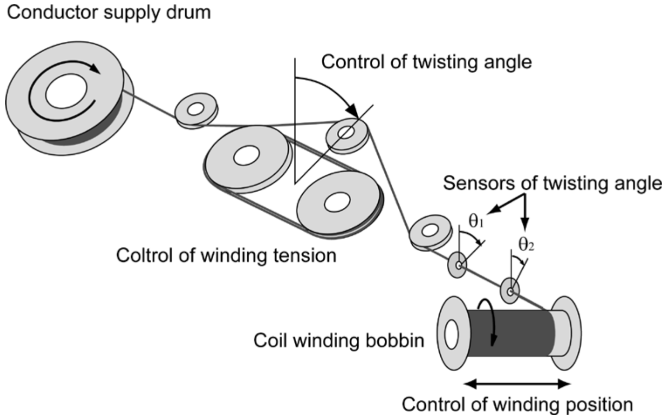

Fig. 3. Principle operation of a twist winding machine.

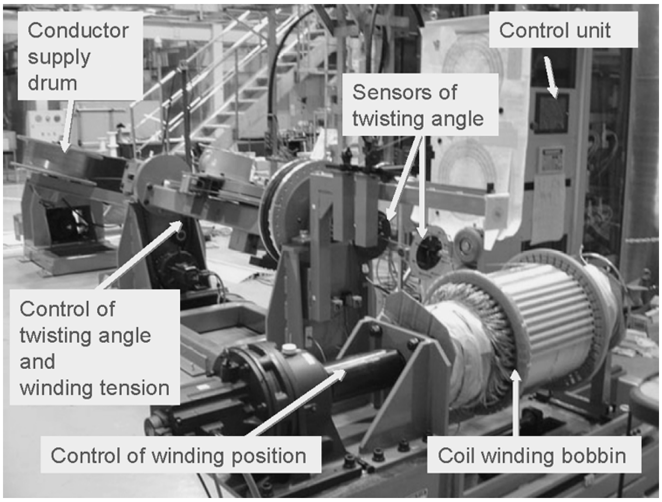

Fig. 4. Winding procedure of the prototype coil by the developed twist winding machine.

can be measured by two angle sensors installed just before the winding bobbin. The angle sensor has a proximity sensor which rotates around the conductor and detects the groove on the conductor. Then the twist angle of the conductor at the position of the winding bobbin is extrapolated from the measured values of two angle sensors. Fig. 4 shows the developed winding machine, which can control the winding tension, the axial position of the winding bobbin and the twist angle of the conductor according to the programmed table, and Fig. 4 also shows the winding procedure of the prototype coil.

B. Winding Procedure of the Prototype Coil

Fig. 5 shows the prototype conduction cooled coil during the winding process. The coil was wound in two weeks at the pace of 1 layer/day. The twisting angle of the conductor was measured every 1/4 turn in the center part and every 1/12 turn in the end part of the coil and was used for the feedback control of twisting angle. Fig. 6 shows the measured errors of the twisting angle of the conductor at the 12th layer of the windings as an example. The errors were within ±10 degrees and their root mean square is 3.1 degrees. The root mean square (RMS) of the twisting angle errors for each layer of the windings were summarized in Table III. The RMS errors were larger then 5 degrees until no. 8 layer of the windings. However after the improvement of the twisting angle control, we have succeeded to develop the twist winding technique with the RMS error less than 5 degrees, which is enough for suppressing AC losses of the coil [2].

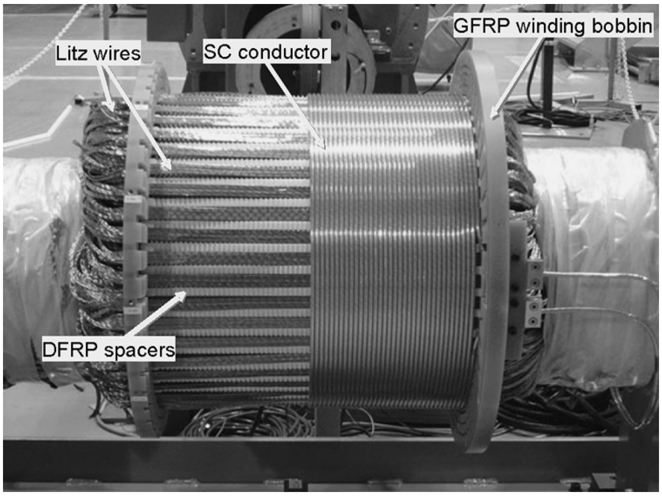

Fig. 5. Prototype conduction-cooled coil during the winding process.

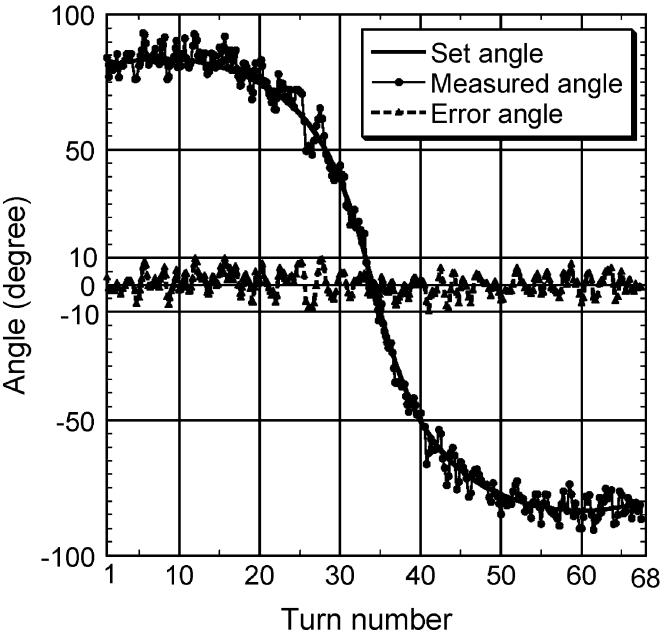

Fig. 6. Measured errors of the twisting angle of the conductor at 12th layer of the windings.

TABLE III
TWISTING ANGLE ERRORS OF EACH LAYER OF THE WINDINGS

Layer No.	RMS angle error (deg)	Layer No.	RMS angle error (derg)
1	4.3	8	9.3
2	5.7	9	3.5
3	6.0	10	3.5
4	5.4	11	3.8
5	5.8	12	3.1
6	5.6	13	3.9
7	5.9	14	3.9

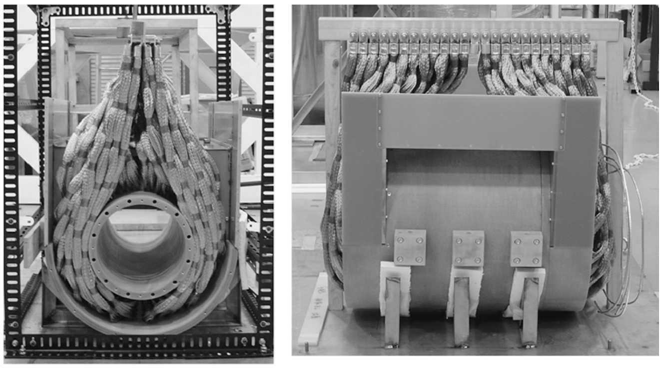

Fig. 7. Prototype coil with the Litz wires for conduction cooling just before epoxy impregnation.

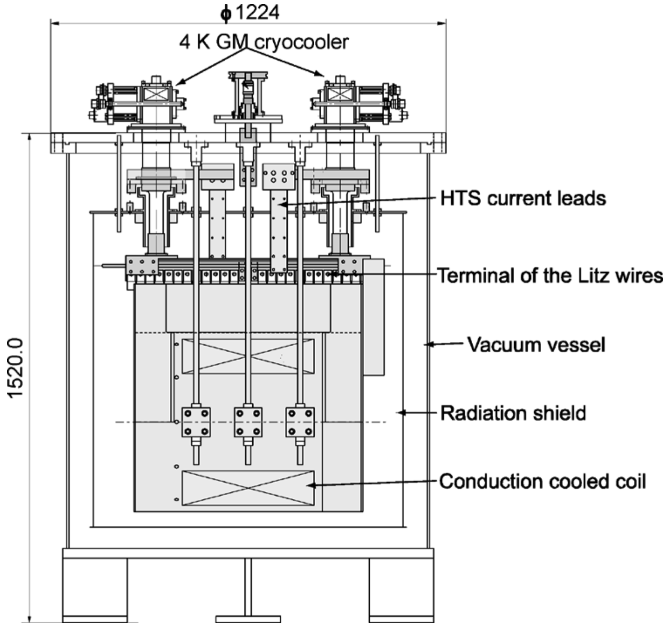

Fig. 8. Cryostat for cooling and excitation tests of the prototype coil.

C. Experimental Setup

Fig. 7 shows the prototype coil after winding and before epoxy impregnation. The ends of the Litz wires were bundled and terminated with solderless contacts. Fig. 8 shows experimental setup for cooling and excitation test. The coil is covered with the radiation shield cooled by the 1st stages of two cryocoolers, and is installed into the vacuum vessel. The terminals of the Litz wires were attached to the cold head of two cryocoolers. The heat loads to the conduction cooled coil and cooling capacity of GM cryocoolers are listed in Table IV. The total copper cross section of the Litz wires is 0.009 548 m^2, and the average length of the Litz wires from the coil to the 2nd stage of the cryocooler is 1.10 m. If the 2nd stage temperature of the cryocooler is estimated to be 4.0 K and the heat input to the coil is 1.8 W, the temperature of the coil can be kept at 4.4 K during the standby operation of the UPS-SMES.

TABLE IV
HEAT LOADS OF THE PROTOTYPE CONDUCTION COOLED COIL

Cooling capacity of two GM cryocoolers	
Cooling capacity of 1st stage (@ 50 K)	120 W
Cooling capacity of 2nd stage (@ 4 K)	3 W
Heat loads @ 50 K	
Copper current leads (1000 A)	84.0 W
Radiation	8.0 W
Supports	1.4 W
Piping, etc.	0.4 W
Total	93.8 W
Heat loads @ 4 K	
HTS current leads (1000 A)	1.0 W
Radiation	0.6 W
Supports	0.1 W
Piping, etc.	0.1 W
Total	1.8 W

The performance of the conduction-cooled pulse coil is determined by the temperature margin during pulse operation. The temperature rise of the prototype coil after 1 sec discharge is estimated as 6.7 K with its current sharing temperature of 8.2 K, assuming an adiabatic condition in which the heat transfer from the SC conductor to the DFRP spacers and other winding components was neglected. The detailed analysis including the heat transfer during the pulse operation has been carried out [3] and the temperature margin was estimated to increase from 1.5 K to 2.5 K. We will perform the verification tests of the prototype coil by the end of 2004.

IV. SUMMARY

We have been developing a conduction-cooled LTS pulse coil as the most reliable and cost effective superconducting coil for the UPS-SMES. The construction of a 100 kJ prototype coil has been successfully achieved by developing the special winding techniques for the conduction-cooled LTS pulse coil. For the next step, 1 MJ conduction-cooled LTS pulse coils are planned to be fabricated during the 2004 fiscal years. In the 2005 fiscal year, the performance tests of the 1 MJ coils will be conducted, and the long-term field test of the UPS-SMES using the 1 MJ LTS pulse coils is planned in the 2006 fiscal year.

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