Validation of the High Performance Conduction-Cooled Prototype LTS Pulse Coil for UPS-SMES

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Abstract—A conduction-cooled low temperature supercon-ducting (LTS) pulse coil has been developed as a key technology for UPS-SMES. We have been developing a 1 MW, 1 s UPS-SMES for a protection from a momentary voltage drop and an instant power failure. A conduction-cooled LTS pulse coil has excellent characteristics, which are adequate for a short-time uninterrupt-ible power supply (UPS). The LTS coil has better cost performance over the HTS coil at present and the conduction cooling has higher reliability and easier operation than the conventional cooling schemes such as pool boiling with liquid helium or forced flow of supercritical helium. To demonstrate the high performances of the LTS pulse coil, we have fabricated a prototype coil with stored energy of 100 kJ and have conducted cooling and excitation tests. The successful performance test results including current shut-off test with a time constant of 1.3 s and repeated excitation of a triangular waveform with high ramp rate are reported.

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

I. INTRODUCTION

UPS-SMES as a protection from momentary voltage drop and power failure are required for 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 [1]–[3]. A five-year project to develop UPS-SMES is being started from 2002 fiscal year as one of the research promotion programs of the New Energy and industrial technology Development Organization (NEDO). We have developed a 100 kJ class UPS-SMES in order to do a principle actual proof [4]. According to the successful results of
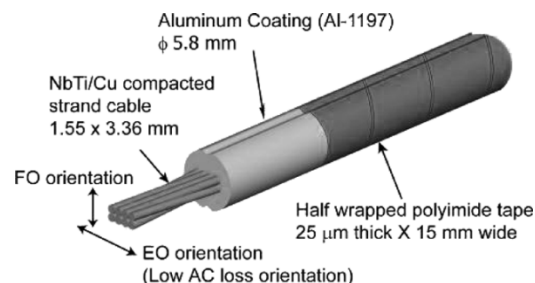
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Fig. 1. Superconducting conductor for the LTS pulse coil.

TABLE I
SPECIFICATIONS OF THE SC CONDUCTOR

Conductor type	Aluminum coated NbTi/Cu compacted strand cable
Conductor diameter	5.8 mm
Operational current	1000 A
Critical current	3740 A @ 5 T, 4.2 K
Coupling time constant of AC loss: $A^*\tau$ [1]	82 msec for face-on (FO) orientation 10 msec for edge-on (EO) orientation
Compacted strand cable	1.55×3.36 mm
Aluminum coating	Al- 1197
RRR of Al coating	9.85

[1] A^* is shape factor of conductor cross-section, τ is coupling time constant [5]

the cooling and excitation tests, we have proceeded to construct 1 MJ LTS pulse coils used for 1 MW, 1 s UPS-SMES.

II. DESIGN AND CONSTRUCTION OF A CONDUCTION-COOLED PROTOTYPE LTS PULSE COIL

A low AC loss and a high stability are required for the super-conducting (SC) conductor of the conduction-cooled LTS pulse coil. The SC conductor of a NbTi/Cu compacted strand cable extruded with an aluminum has been developed as shown in Fig. 1 and its parameters are listed in Table I. The conductor has the anisotropic AC loss properties depending on the orien-tation of the time varying magnetic field. The AC loss becomes the minimum when the magnetic field is applied parallel to the flat surface of compacted strand cable (EO orientation) 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 [5].

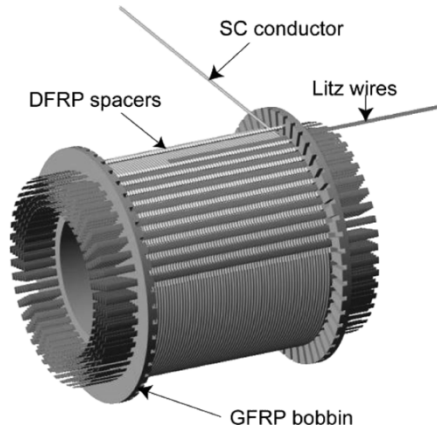| Dimension of the coil windings	
Inner diameter: 2a1	0.305 m
Outer diameter: 2a2	0.509 m
Length: 2L	0.402 m
Total turn number	67 turns x 14 layers = 938 turns
Coil inductance	0.20 H
Maximum magnetic field	2.2 T
Magnetic stored energy	100 kJ
Operating current	1000 A
Coil weight	400 kg

Fig. 2. Structure of conduction-cooled LTS pulse coil.

The coil shape is a single solenoid of 67 turns $\times$ 14 layers wound on the GFRP bobbin using the specially developed automatic twist winding machine and its parameters are listed in Table II. 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. 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. The total copper cross-section of the Litz wire is 4,774 mm^2.

III. COOLING AND EXCITATION TESTS

A. Experimental Set-Up

Fig. 3 shows the inside of cryostat for performance tests. A conduction-cooled LTS pulse coil was connected with two GM cryocoolers which have cooling capacity of 3 W at 4 K and 120 W at 50 K. Temperature sensors were placed as shown in Fig. 4 within the coil windings, thermal radiation shields and the cold heads to monitor the temperatures during cooldown and excitation tests. In addition, the heaters were attached at the inner surface for the thermal characterizations. The coil was placed in the cryostat and evacuated for the performance test.

B. Cooling Test

Two different cooldown schemes were conducted to investigate thermal performance of the coil; a precooling with a liquid nitrogen and without it. As utilizing a LN_2, the cooldown of
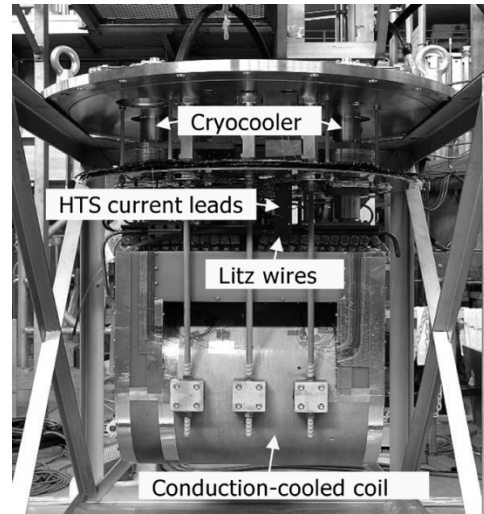

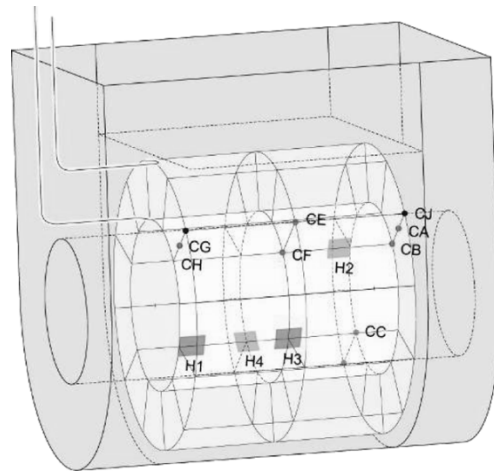Fig. 3. Cooling and excitation test set-up of conduction-cooled LTS pulse coil.

Fig. 4. Temperature sensors (CA–CJ) and heaters (H1–H4) within the coil.
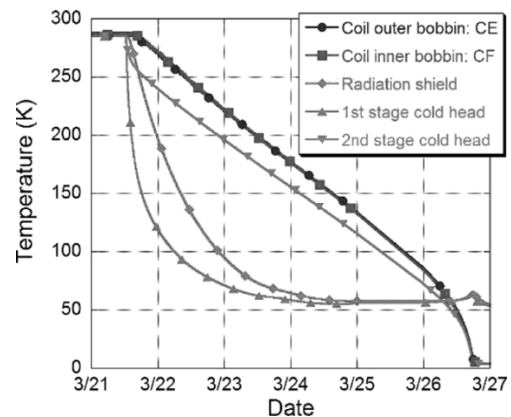

Fig. 5. Cooldown curve of conduction-cooled coil with cryocoolers.

the system was achieved within three days of operation, while it took approximately five days to cooldown the system as exclusively utilizing cryocoolers (See Fig. 5). In both cases, the spatial temperature distributions within the coil were negligible and the coil temperatures reached below 4 K, which demonstrated the good thermal performance of the coil.
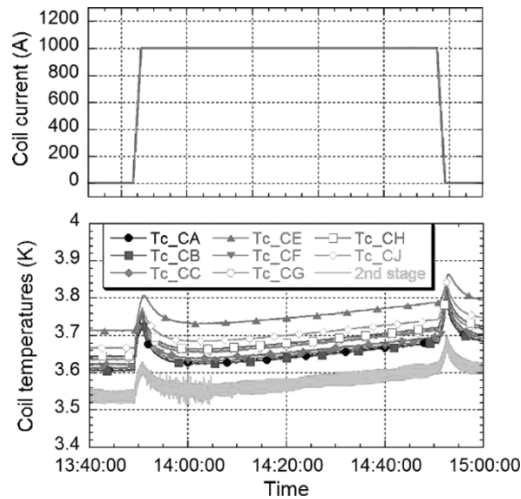
Fig. 6.   Performance test results applying a rated current of 1000 A for an hour.
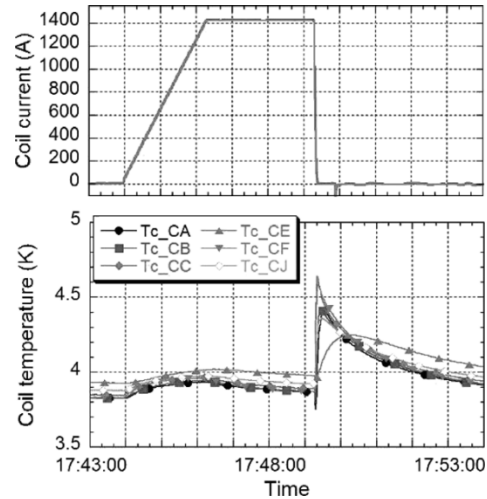

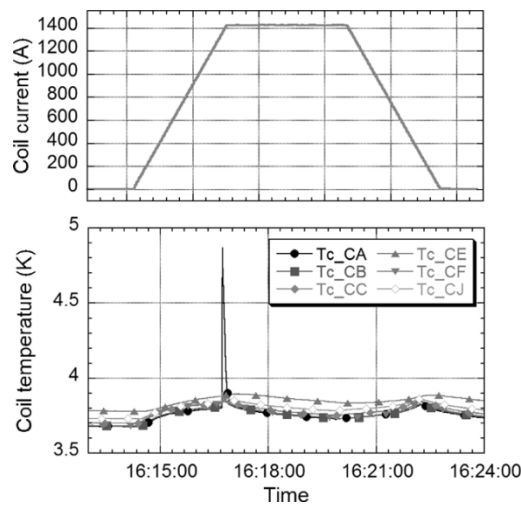Fig. 8.   High speed current shut-off test from 1420 A with time const. of 1.3 s.

Fig. 7.   Over-current test of 1420 A with a stored energy of 200 kJ.

C. Rated Current Test

The excitation test was performed as the system reached the steady-state condition. Fig. 6 shows the performance test results. As applying a rated standby current of 1000A for an hour, the temperatures within the coil was gradually increased. The slopes of temperature curves were almost identical within the coil winding, which also corresponded to the temperature increase at the cold head of cryocoolers. The results indicated that the design of a coil was proved to be sufficient to sustain stable operation with a rated current during a standby state.

D. Over-Current Test

Since the prototype showed a very stable operation under a rated current of 1000 A, the test was continued to examine the maximum operating current. Fig. 7 shows the performance test with the maximum current, 1420 A and a stored energy of 200 kJ. One of the temperature sensors measured a sharp temperature increase up to 4.9 K corresponding to a crack of epoxy resign due to the large electromagnetic force during ramp up to 1420 A. However there was no sign of the coil quench. The coil

has been excited up to 1420 A repeatedly and was stably operated for one hour. The prototype proved its high potentiality of operation.

E. High Speed Shut-Off Test

To validate the thermal performance of the coil, the coil current was reduced rapidly from 1000 A, 1230 A and 1420 A to 0 A with a time constant of 1.3 s. Fig. 8 shows the temperature increase in the coil during the discharge from 1420 A. The AC losses of discharges from 1000 A, 1230 A and 1420 A are 147 J, 210 J and 278 J, respectively. The temperature increase within the coil was less than 0.8 K so that the heat generated by the AC loss was well distributed within the coil winding. Since the actual system is operated with 1 s discharge mode from 1000 A to 707 A (half of the magnetic stored energy), the test results exceed the expected performance of the coil.

F. Repeated High Speed Excitation Test

A high thermal diffusivity of the coil was demonstrated with a repeated excitation test. The current was repeatedly increased or reduced from 0 A to 1000 A with a ramp rate of 35 A/s, 50 A/s and 75 A/s. Fig. 9 shows that the total of 20 excitations of 50 A/s was conducted with 1.1 K of the coil temperature increase. The AC loss powers of the repeated high speed excitation up to 1000 A with the ramp rate of 35 A/s, 50 A/s and 75 A/s were 1.2 W, 1.9 W and 2.9 W, respectively. Whereas the measured temperature increases in the coil were 0.7 K, 1.1 K and 1.4 K, which reveals a good thermal diffusivity of coil winding. Consequently, the coil has a potential to perform stable condition even under continuous pulse operations.

IV. DISCUSSION

The design of conduction-cooled pulse coil is determined by the temperature margin during pulse operation. The temperature increase of the prototype coil after 1 s discharge is estimated as 6.7 K assuming an adiabatic condition in which the heat transfer from the SC conductor to the DFRP spacers and other winding components was neglected. According to the performance test, the prototype demonstrated its high potentiality for
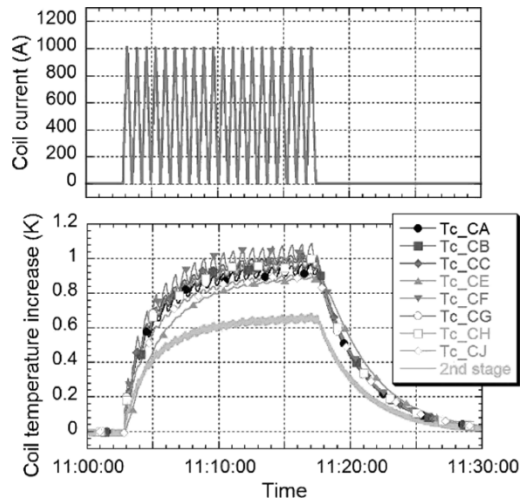
Fig. 9. 20 times repeated high speed excitations test increased or reduced from 0 A to 1000 A with a ramp rate of 50 A/s.

Fig. 11. Time constants of thermal diffusivities for each component with the total amount of thickness in the coil, where stainless steel (10mm) is indicated for reference and was not used in the coil.
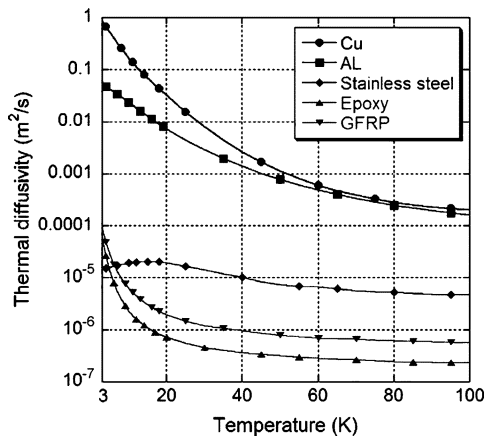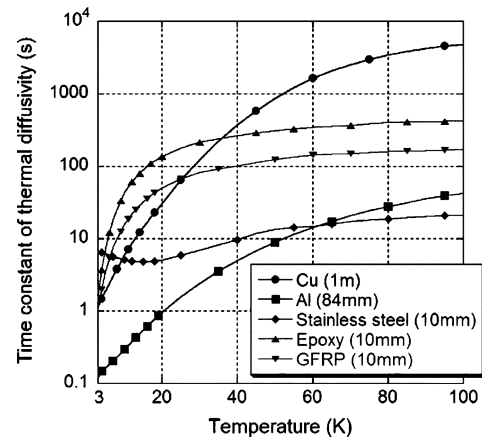

Fig. 10. Thermal diffusivities of materials in the coil, where stainless steel is indicated for reference and was not used in the coil.

the SMES applications. In fact, the performance values well exceeded the prototype design. Thus, the compact design of an actual system can be achieved and the running cost will be substantially reduced. Effective thermal design, arrangement of bundled Litz wires, leads to these high performances of the prototype. Further, the supporting structure with Dyneema FRP (DFRP) spacers in the coil winding enhances the thermal performance.

Since the coil consists of copper, aluminum, epoxy resign and DFRP, these materials have relatively high thermal diffusivities below 10 K as shown in Fig. 10. The time constants of thermal diffusivities for each component with the total amount of thickness used in the coil are estimated approximately 1 s around 4 K as shown in Fig. 11. Therefore, the heat generated within the coil was dissipated within the winding with a very short period.

So, the spatial temperature distribution within the coil becomes negligibly small against heat generations. The detailed analysis including the heat transfer during the pulse operation and the comparison with the experimental data have been carried out in the related paper [6].

V. SUMMARY

We have successfully developed the conduction-cooled prototype LTS pulse-coil for UPS-SMES. The performance tests validate the design and fabrication technique of the coil. As a matter of fact, the data exceeded the design performance such as; the stored energy was 200 kJ instead of design value of 100 kJ. Since the coil was designated for a pulse operation, the effective thermal diffusivity results in the rapid temperature stabilization. Consequently, the design philosophy has been established and the much compact system with a high efficiency can be developed.

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