Research and Development of Superconducting Magnetic Energy Storage system(SMES)

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Abstract

This paper describes a collaborative work between SEI and KEPCO on the Superconducting Magnetic Energy Storage system (SMES). We have studied two types of magnets. One is the 400kJ class LTS-SMES for testing the power stabilization operated at liquid helium temperature (4.2K) and the other is the 100J class HTS-SMES for confirming the possibility of applying HTS wire to SMES at liquid nitrogen temperature (77k). In this paper, the design of the magnet and the test results are described. Each magnet performed completely at rated operation.

Introduction

SMES has been studied and developed for one of the power application systems using superconducting technology and is expected to be applied for energy storage, stabilization of power system, compensation for short interruption of power for electrical equipment (micro SMES), etc. First, the LTS SMES is described. During the past recent decade, we developed a 400kJ class test magnet for SMES using a metallic superconducting wire operating at liquid helium temperature for investigating the possibility of applying it lo power system stabilization, and its features have been measured [1][2]. More details are described in section 1.

Next, the development of the SMES using HTS wire is described. Recently, HTS superconducting wire operating at 77K with sufficient length and improved characteristics have been obtained [3], so we started studies on the HTS SMES to investigate whether the HTS wire is applicable to the SMES or not. HTS wires can operate at liquid nitrogen temperature (77.3K) so it has the possibility to unprove the reliability of the SMES system and to reduce running costs. The target for energy storage value was set to 100J and prototype magnet was developed [14]. Characteristics and test results of the magnet are described in section 2.

1. LTS SMES

1.1 Magnet Design

Fundamental specification of the test magnet was determined (table 1) in consideration of the magnet size, test scale etc. According to the fundamental specification, the magnet was designed for each component, conductor, coil, vessel, power lead and so on. In this paper, some results of the design are described as follows.

Table 1. Design of prototype magnet

Energy storage	400kJ
Opening current(DC)	350A
Current density of the coil	approx. 50A/mm
Inductance	6.9H
Magnetic field	5T max
Excitation ramp ratio	35A/sec(0.5T/sec)
Applied voltage	400V max

1.1.1 *Coil size*

According to the specs shown in table 1, we started to design the magnet. At First, we determined a rough size of the coil. From the relation with the operating current and current density, and setting the cooling channel occupation ratio to be 50%, area of the conductor was estimated as $3.5mm^2$ Using this result with maximum magnetic field and storage energy, coil size was designed approximately as shown in table 2. For easy handling, *a solenoid coiling* method was selected.

Table 2. Initial coil design

Inner diameter	350mm
Outer diameter	640mm
Height	200mm

1.1.2 Conductor

When power input-output on SMES occurs, the loading current and magnetic field of the magnet are changed and an alternative current energy loss is generated (AC loss). AC loss causes a decrease in efficiency and an increase in instability of the operation. The AC loss in the conductor consists of hysteresis loss, coupling loss, and eddy current loss. To reduce the hysteresis loss, the filament diameter must be fine; and to reduce the coupling loss and eddy current loss, the filament twist pitch should be short and have a high resistance between NbTi and matrix. In order to improve the characteristics, low-AC loss superconducting wire with NbTi/Cu/CuNi monolithic construction was designed and developed as shown in table 3.

1.1.3 Cooling channel

A Cooling channel is required to prevent a coil from the transition from superconducting to a normal state. To investigate the effect of the channel, the fundamental characteristic was tested. Figure 1 shows the cooling characteristics of the test coil with Cu conductor (I.D.81×O.D.118×H50mm) which includes various thickness of the cooling channel as 0.2, 0.3, 0.5 and 1mm. The AC

Table 3 Specification of the conductor

Size	1.1mm×2.5mm
Composition	Nbti:Cu:CuNi=1:2.7:4.6
Number of filaments	26754
Filament diameter	3.8 ㎛
filament twist pitch	20mm
Jc	1300A/m' at 5T
Ac across	0.7kW/ at 0.5T/sec, 01⇔T

loss was simulated by loading current to the conductor, and by increasing the heat flux, temperature of the conductor changed drastically. It is thought that liquid helium change from the nuclear boiling state to the film boiling state at that point.

In addition, stability of the 400kJ magnet was investigated both by the calculation and the experiment of the test coil. As a result, it was confirmed that the cooling channel must be more than 1mm. Therefore, the thickness of the channel was set to be 1mm and the coil size was set to be I.D. 340mm×O.D.582mm×H.200mm.

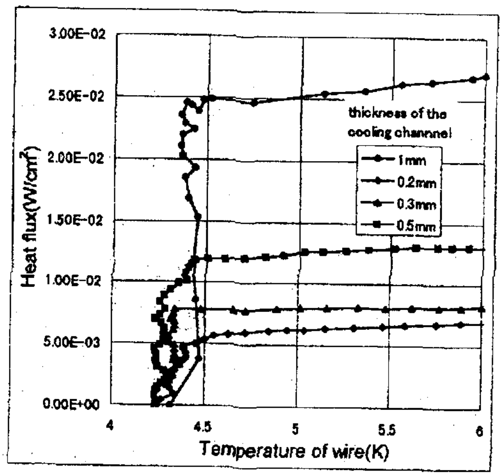

Figure 1. Heat flux test with various channel thicknesses

1.1.4 HTS power lead

Next, we developed a 500A class current lead using HTS superconducting wire to reduce heat leakage from the power terminal at about 30% of Cu leads. Figure 2 shows a configuration of the HTS current leads. Each unit is fixed to the GFRP rods with epoxy resin for reinforcing the HTS wires mechanically. In addition, current leads have a temperature gradient from 4.2K to 77K in operation so the number of the layers of the HTS wire was to be optimized for minimizing the heat leakage. Characteristics of the HTS power lead is shown in table 4.

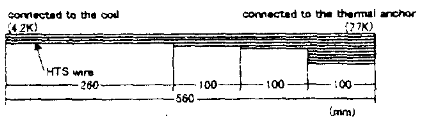

Figure 2. Configuration of the HTS power leads

Table 4 Characteristics of the HTS power leads

Max. current (A)	500
Heat loss (W/leads at 350A)	0.28

1.2 Fabrication of the SMES

After designing the components of the magnet, 400kJ class SMES was fabricated successfully as shown in figure 3 and the magnet operated with a rated 350A DC-current and 420kJ was stored stably.

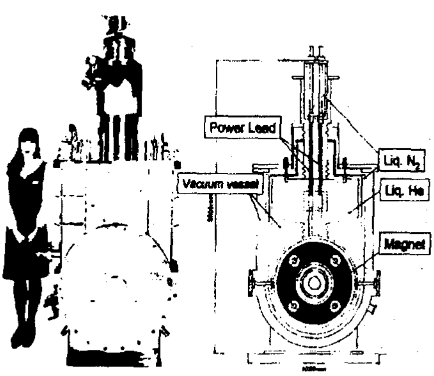

Figure 3. Overview of the LTS SMES

1.3 Test results

Using the fabricated magnet with the other two magnets, the stabilization tests were performed with a simulated power line and it was confirmed that the SMES had potential for stabilizing the fluctuation of the power system. Figure 4 shows the results of the 3-phsase short circuit test. When the SMHS is active, the power fluctuation of the generator is converging within 2 seconds.

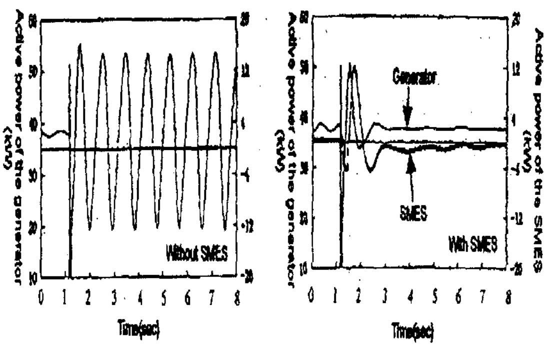

Figure 4. 3-phase short circuit test

Next, the heat loss test was achieved. It operated at max. 0.5 T/s excitation ramp speed and characteristics of the heat loss versus ramp speed were observed as shown in figure 5. Additionally, a heat loss estimation was evaluated and the error of the calculation was obtained to be about 15 to 20% at each ramp speed.

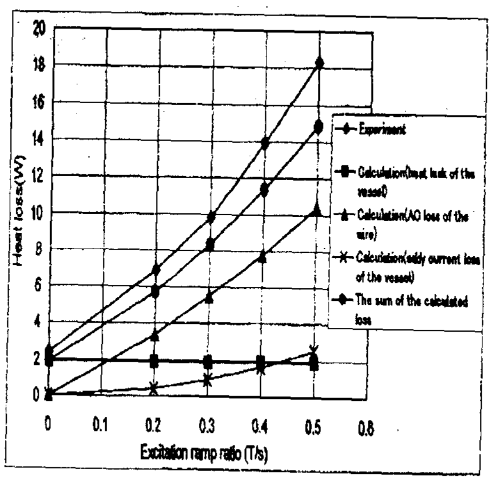

Figure 5. Heat loss test and estimation

Finally, efficiency of power input-output on the magnet alone was calculated to be 86% at full-time operating 50A⇔330A, 0.5T/sec and cooling efficiency set to be 1/350.

2. HTS SMES

To investigate the possibility of applying the SMES using high-Tc superconducting wire (HTS wire) for power system utility, plans were initiated to manufacture the HTS test coil for searching various characteristics of HTS SMES operating at liquid nitrogen temperature.

2.1 Design the coil

The energy to be stored was determined to be 100J and in order to design the coil, basic characteristics, such as mechanical properties and critical current density of the high-Tc wire and cooling characteristics were measured as follows.

2.1.1 Cooling Channel

The performances of some cooling channels of the HTS-SMES were also investigated. The heater power at the transition points in each case are indicated in Table 5. It was confirmed that the heal flux at the transition point in the case of the horizontal cooling channel is about 1/20 less than the critical heat flux of atmospheric liquid nitrogen. [5]

Table 5. Heater power per unit area at the transition point

Channel thickness	Horizontal direction	Vertical direction
0.5mm	1.0 W/cm^2	6 W/cm^2
1.0mm	1.3 W/cm^2	10 W/cm^2

2.1.2 Stability of the coil

We have investigated the characteristics of AC loss Using a small coil with HTS wires [6]. And as a result, the maximum AC loss density of 100J SMES coil was estimated to be about 3.2×105 (W/m3 where a maximum magnetic field of 0.4T is applied with the operating frequency of 1 Hz. The Cooling channel is made by installing spacers with a gap between each other and the occupation ratio of the cooling channel was set to be 50%. In this case, the heat per unit cooling area is about $0.01 W/cm^2$ when cooling channels with spacers of 0.5mm are made between turns, and about $0.15 W/cm^2$ when they are made between pancakes. In both cases, the heat generated by AC loss Is much less than the critical heat flux. Therefore, the structure of cooling channels for 100J coil was determined to install spacers of 0.5mm thickness between pancakes.

2.1.3 Design of coil operation

The packing factor of the coil is calculated with about 0.6 in consideration of the spacer and the coil insulation tape thickness. The conductor is composed of three bundled high-Tc super-conducting wires in order to larger operation current. The pancake shape was determined to have the inner diameter of 80mm considering the bending distortion of the wire. The outer diameter of the pancake and the number of pancakes to be stacked were determined by calculation so that the coil to store the required energy is constructed with minimum length of the wire. Considering the Ic-B characteristics of the wire. Finally, the design value of 100J coil shown in Table 6 was obtained. Figure 6 shows the loadline of the test coil at 77.3K.

Table 6. specification of 100J/77.3K HTS test coil

Wire and size (mm)	Bi-2223 Ag-sheathed Multifilamentary tape (61 filaments) 0.25t×3.8w 3 bundle
Number of coils	10 double pancakes
Size of magnet (mm)	I.D.800×O.D.200×height 93
Clear bore (mm)	φ 42
Operating current (A)	34.2(at 77.3K)
Inductance (H)	0.171
Magnetic field (T)	Bo=0.40 Bmax=0.42
Stored energy (J)	100(at 77.3K)
Total length of wires (m)	Approx. 2,100
Total weight (kg)	Approx. 20

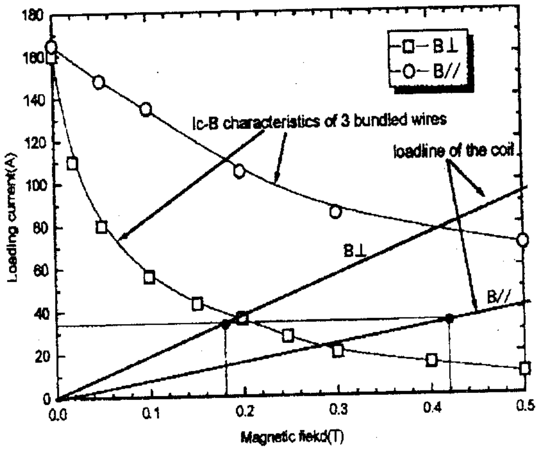

Figure 6. Coil loading

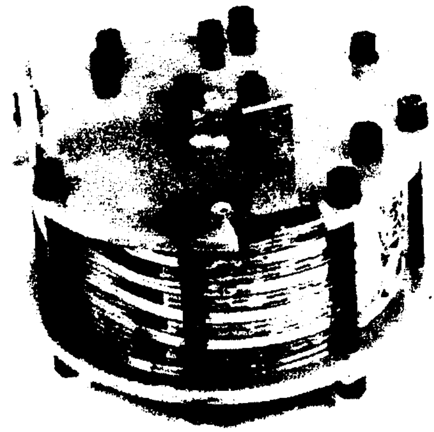

Figure 7. photograph of completed coil

The test coil, which used a long-sized wire of Jc=20,000~22,OOO A/㎠was engineered so that 100J of energy can be stored in the bath cooling operation of the liquid nitrogen (at 77.3K). The inductance of the test coil was 0.171H, which corresponds to 100J of energy at the current of 34.2A. This rated current is 90% of the Ic level. The current density of the test coil was 8.9 A/㎟

2.2 Fabrication of the coil

100J coil was manufactured according to the above-mentioned design. The test coil has 10 double pancake coils stacked, and is comprised of GFRP-made components such as the bobbin, the flange, and the spacer. Figure 7 shows the view of the test coil. The test coil has a conductor made of a bundle of three Ag-sheathed multi-filamentary wires of Bi-2223 series, which is wound on the bobbin with a diameter of 80mm with the double pancake winding method.

For coil winding, a winding tension was applied to each of the 3 wire bundles. This winding tension was regulated in the range of 1 kg/mm2± 10% when it was applied to the wire to avoid an Ic deterioration that may result from a possible strain incurred during the coil winding. A 0.5mm thick cooling channel was set between the coils to improve the cooling characteristic.

2.3 Loading test

We conducted DC and AC current tests on the coil both at 77.3K (bath cooling in liquid nitrogen) and a low temperature (25-30K), as well as measuring the corresponding AC losses. In the DC current test at 77.3K, a holding was set to ensure the achievement of 100J energy storage at the rated current of 34.2A. The AC current was a triangle wave with peaks of 34.2A, and at each frequency of 1 Hz and 2Hz, the current loading continued up to 34.2 A, demonstrating no trouble involved. The current loading test at a low temperature was conducted as a verification test in which the energy storage of up to 1KJ was confirmed by cooling the entire coil to 25-30K with the evaporative He gas, and then by applying a DC current of up to 110A in that temperature condition. The design storage energy of the coil for low temperatures was 7KJ. The 4-temrminal method was used for the measurement of an AC loss in which the current was applied at a triangle wave of the I/O current waveform during SMES operation. Figure 8 shows the measurement result concerning the AC loss at 77.3K. We measured at a frequency of up to 20Hz, and learned that the AC losses for every frequency and current value are proportional to about 2nd power of the loaded current, and are proportional to about 1st power of the operated frequency.

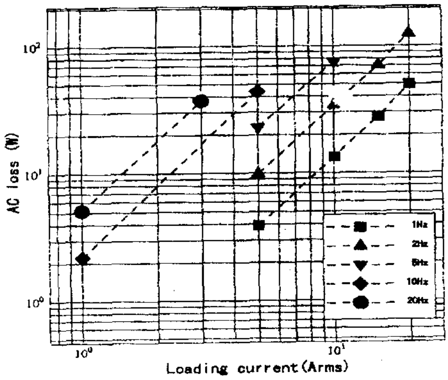

Figure 8. AC loss of 100J/77.3K HTc test coil

Conclusion

On LTS SMES, the effect of the stabilization of a simulated power system was confirmed. Also, the estimation of the heat loss was evaluated and it was confirmed that it had good accuracy. On HTS SMES, we fabricated a test coil that uses a high-Tc superconducting wire, and successfully verified that the coil can store 100J of energy in a liquid nitrogen operation for the first time in the world. We also experimented further to witness the energy storage of up to 1KJ, which proved that the high-Tc superconducting coil allows a stable operation even at low temperatures.

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