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Electrical insulating design of 600kJ conduction cooled HTS SMES

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Abstract-- **The electrical insulation design and withstanding test of mini-model coils for 600 kJ class conduction cooled high temperature superconducting magnetic energy storage (HTS SMES) have been studied in this paper. The high voltage is generated to both ends of magnet of HTS SMES by quench or energy discharge. Therefore, the insulation design of the high voltage needs for commercialization, stability, reliability and so on. In this study, we analyzed the insulation composition of a HTS SMES, and investigated about the insulation characteristics of the materials such as Kapton, AlN and vacuum in cryogenic temperature. Base on these results, the insulation design for 600 kJ conduction cooled HTS SMES was performed. The mini-model was manufactured by the insulation design, and the insulation test was carried out using the mini-model.**

1. INTRODUCTION

The Superconducting Magnetic Energy Storage (SMES) is one of direct electrical energy storage systems. The main advantage of SMES over other storage systems is the high power and energy density with excellent conversion efficiency, greater than 96%. The number of charge-discharge cycles is nearly infinite. A SMES requires a low maintenance and dose not use any noxious material [1]. After the discovery of the high temperature superconductor (HTS) its successful fabrication into useful conductors has promised a great technical advance in numerous industrial areas, mainly because of the easy and economical cooling with liquid nitrogen at around 77 K [2].

On the other hand, the conduction cooled high temperature superconducting (HTS) SMES discussed in this paper operates at 25 K, is conduction cooled with cryocooler(s), and does not employ liquid helium [3-5]. Because of the increase of specific heat with increasing temperature, a given heat load causes a smaller temperature rise in a high temperature magnet than a lower temperature (~ 4 K) magnet [3]. Especially the need to protect the cryocooler and to compact of the system has led to the consideration of the condition as insulators [6].

In this study, we studied on the electrical insulation design of 600 kJ conduction cooled HTS SMES. Table 1

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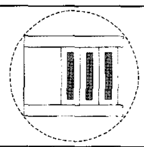
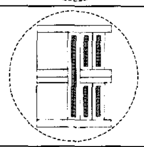
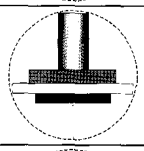
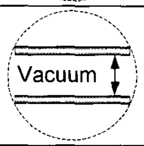
TABLE I
INSULATION COMPOSITION OF 600 KJ HTS SMES.

Composition	Shape	Discharge type
Turn-to-turn (A)		Breakdown
Layer-to-layer (B)		Surface
Cryocooler-to-magnet bobbin (C)		Breakdown, Surface
Cryocooler-to-current lead (D)		Breakdown, Surface
Magnet bobbin-to-cryostat (E)		Breakdown
Current lead-to-lead (F)		Breakdown

shows the insulation composition of 600 kJ conduction cooled HTS SMES. The composition of insulation consisted of turn-to-turn (part A), layer-to-layer (part B), cryocooler-to-magnet bobbin (part C), cryocooler-to-current lead (part D), magnet bobbin-to-cryostat (part E), and current lead-to-lead (part F) insulation and so on. The mini-model was manufactured, we tested that, and we confirmed the DC breakdown voltage more than 4 times of the operating voltage.

2. EXPERIMENTAL

The experimental setup consisted of cryostat, cryocooler, vacuum apparatus, voltage source and electrode systems.

The cryostat was made of stainless steel, by 300 mm inner diameter and 900 mm high. It consisted of vacuum section and thermal insulation section to prevent heat invasions. The cryocooler, vacuum exhaust part and high voltage supply part are attached to flange that is its upper part. Fig. 1 shows electrode systems for the characteristics of turn-to- turn (a), surface flashover (b), breakdown of

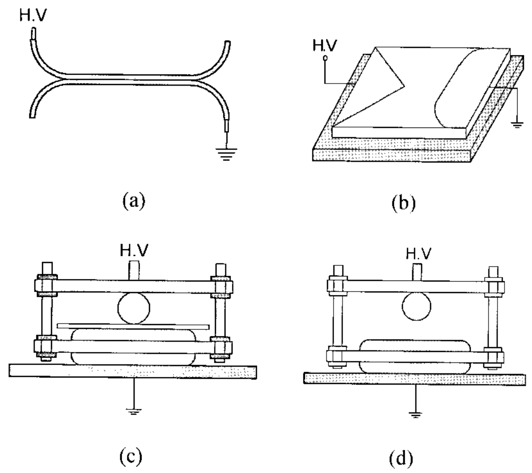


Fig. 1. The electrode systems (a) turn-to-turn (b) surface flashover (c) breakdown of AlN (d) vacuum breakdown.

Aluminum Nitride (AlN), Kapton and Al_2O_3 (c), vacuum breakdown (d). The electrode systems were taken the place in the cooling head of cryocooler. The turn-to-turn insulation was wrapped by Kapton tape (thickness: 0.025 mm, width: 10 mm). Wrapping number on the copper wire are 1, 2 and 3, respectively. In surface flashover insulation, the tip angle of triangle electrode was 45 degrees. Also, the curvature radius of plane electrode was 10 mm to prevent the concentration of electric field at edge. The breakdown insulation was used AlN and vacuum. The diameter of upper part sphere electrode was 10 mm and the diameter of lower plane electrode was 40 mm. Both electrodes were made of stainless steel.

The cryocooler is single stage Gifford–McMahon (GM) cycle cryorefrigerator (model: AL300, CRYOMECH Co.), and used cooling temperature of cooling head is 40 K. The maximum arrival degree of vacuum is 1.3×10^{-6} torr. And dc high voltage (max. 100 kV) was supplied. The experiments were repeated 10 times for each sample to obtain 0.1% value of Weibull probability of discharge voltage. The vacuum and cryogenic temperatures inside cryostat were fallen to 2×10^{-6} torr and 45 K from atmospheric, respectively. Mini-model is manufactured by copper conductor, Kapton tape and AlN etc.

3. RESULTS AND DISCUSSION

Fig. 2 shows Weibull probability distribution of breakdown properties of Kapton. When Kapton tape wrapping were changed to 1, 2 and 3 times, the maximum breakdown voltage with 0.1% of Weibull probability are 2.48 kV, 6.54 kV and 11.48 kV, respectively. Magnet bobbin is metal of brass and floating state. And maximum output voltage of AC/DC converter is DC 3 kV. The standard withstand voltage decided by DC 9 kV that is 3 times with margin of maximum output voltage of the converter. Therefore, Kapton wrapping for turn-to-turn insulating is 30% overlapped 3 layers with 0.025 mm thickness and 10 mm width.

The magnet bobbin and current lead of conduction cooled HTS SMES consisted of the metal that has superior thermal-conductivity for cooling of coil [7]. Thus, between cooling head of cryocooler and magnet/current lead must insert insulating material. In addition, it must have high thermal conductivity for efficient cooling when it is general operating state. Therefore, we choose to AlN that expected using between cooling head and magnet/current lead, and its insulation properties was studied.

Fig. 3 shows Weibull probability distribution of surface flashover and breakdown properties of AlN. The surface length and thickness of AlN sample are 6 mm and 1 mm, respectively. As shown in Fig. 3, the maximum surface flashover strength with 0.1% of Weibull probability is 1.16 kV/mm. The maximum withstanding voltage of 600 kJ class SMES is DC 9 kV. Therefore, flashover insulation length is 7.8 mm. And the maximum breakdown strength with 0.1% of Weibull probability is 35.65 kV/mm. So breakdown insulation thickness is about 0.3 mm. The insulation design of the parts C and D must take care of breakdown than surface flashover.

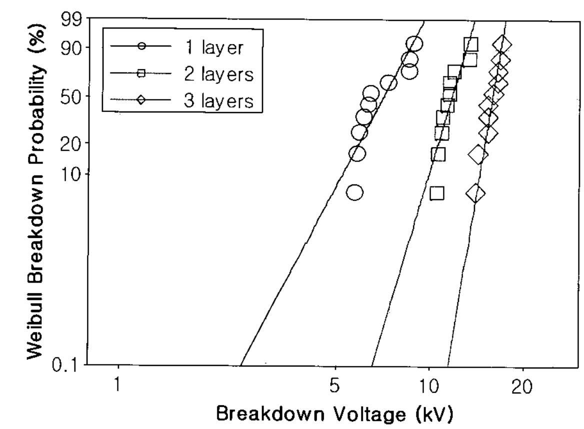


Fig. 2. Breakdown properties of Kapton.

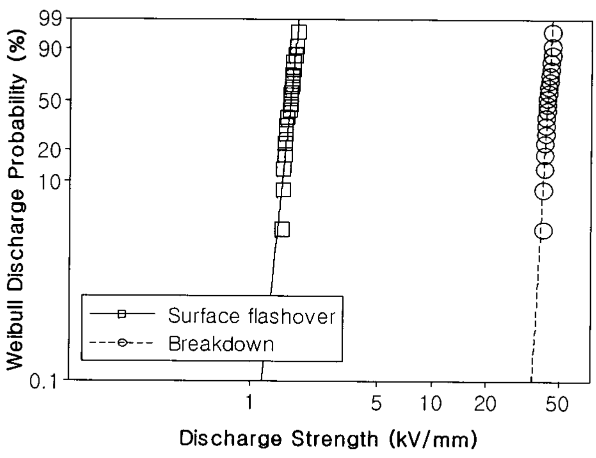


Fig. 3. Surface flashover and breakdown properties of AlN.

Fig. 4 shows the dependence on breakdown strength of AlN, Al_2O_3 and Kapton. As shown in Fig. 4, the breakdown strength of Kapton is higher than the others. On the other hand, however, the thermal conductivity of Kapton is lower than the thermal conductivity of AlN and Al_2O_3 [8-9]. Therefore, we have chosen AlN for insulating between cryocooler and magnet/current lead.

The parts E and F depended on breakdown strength of vacuum at cryogenic temperature. The operating condition of conduction cooled HTS SMES is 10^{-6} torr and 40 K. Fig. 5 shows Weibull probability distribution of breakdown properties at vacuum. As can be seen in Fig. 5, when electrode gaps were changed to 3 mm and 5 mm, the maximum breakdown voltage with 0.1% of Weibull probability are 15.49 kV and 21.94 kV, respectively. Therefore, breakdown insulation gap in vacuum is about 2.1 mm.

The basic insulation design for 600 kJ class SMES on the basis of these results is summarized in Table 2. The results of Fig. 2, 3, 4 and 5 were obtained only calculation by Weibull distribution probability. In the case of conduction cooled SMES, stress may be applied between cooling head and magnet bobbin.

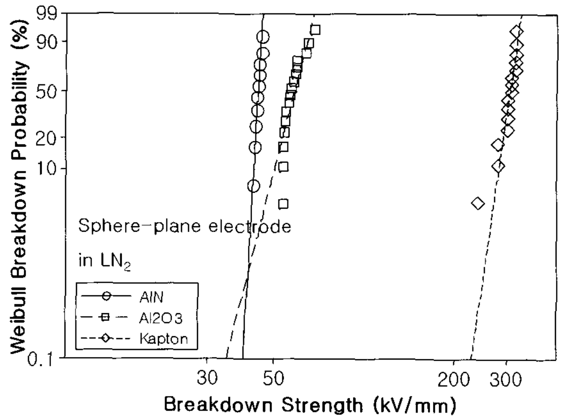


Fig. 4. Dependence on breakdown strength of AlN, Al_2O_3 and Kapton.

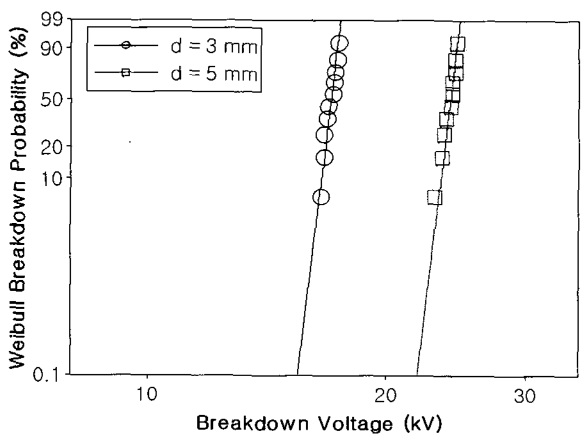


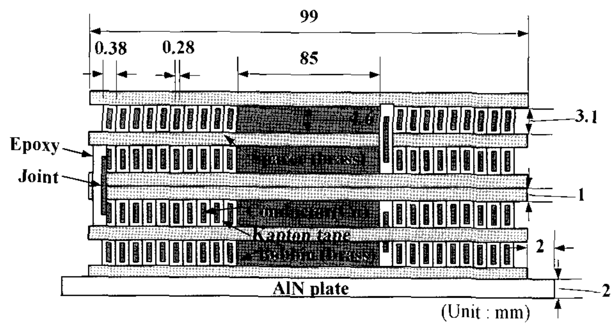
Fig. 5. Breakdown properties of vacuum.

Therefore, insulation design of mini-model HTS SMES has to consider the mechanical margin. And the margin of AlN was considered not only the mechanical properties but also the difficulty of a manufacturing process. And the other parts are considered the oscillation of the magnet.

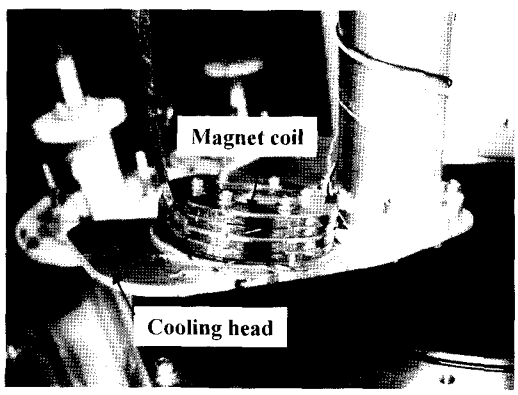
The insulation mini-model was manufactured on the basis of the results of Table 2. Fig. 6 shows the structure (a) and photograph (b) of manufactured mini-model. The insulation test of the mini-model was done and the breakdown voltage of the mini-model is 9 kV that is about triple of withstand DC 3 kV. The breakdown occurred at Kapton film of the turn-to-turn insulation.

TABLE II
BASIC INSULATION DESIGN FOR 600 KJ SMES.

Composition	Material	Insulation design specification
Turn-to-turn (A)	Kapton	Turn-to-turn insulation was combined layer-to-layer insulation.
Layer-to-layer (B)	Kapton	3 layers, 30% overlapping (T:0.025mm, W:10mm)
Cryocooler-to-magnet bobbin (C)	AlN	Thickness 0.3mm, Collar length 7.8mm
Cryocooler-to-current leads (D)	AlN	
Magnet bobbin-to-cryostat (E)	Vacuum	Distance for insulation is 2.1mm.
Current lead-to-current lead (F)	Vacuum	



(a)



(b)

Fig. 6. The Mini model (a) structure (b) photograph.

4. CONCLUSION

In this paper, we classified insulation composition into six categories, based on the type of discharge property and insulating material.

Kapton wrapping for turn-to-turn and layer-to-layer insulation is 2 layers, the insulation length and thickness of AlN for cryocooler-to-magnet bobbin and current lead insulation are 3.9 mm and 0.13 mm. And insulation length of vacuum for magnet bobbin-to-cryostat insulation is 1.1 mm. However, the design has to consider margin and mechanical properties.

The mini-model was manufactured that was considered to mechanical properties and margin. It withstands about 9 kV that is triple of maximum output voltage.

Hereafter, we are going to study on insulating properties considered to thermal and mechanical properties.

ACKNOWLEDGMENT

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