Journal of the Korea Institute of Applied Superconductivity and Cryogenics
Vol.7, No.2, (2005), pp.39~43

Insulation Characteristics for a Conduction-Cooled HTS SMES

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***Abstract*— Toward the practical applications, on operation of conduction-cooled HTS SMES at temperatures well below 77 K should be investigated, in order to take advantage of a greater critical current density of HTS and considerably reduce the size and weight of the system. Recently, research and development concerning application of the conduction-cooled HTS SMES that is easily movement are actively progressing in Korea. Electrical insulation under cryogenic temperature is a key and an important element in the application of this apparatus. However, the behaviors of insulators for cryogenic conditions in air or vacuum are virtually unknown.**

Therefore, this work focuses on the breakdown and flashover phenomenology of dielectrics exposed in vacuum for temperatures ranging from room temperature to cryogenic temperature. Firstly, we summary the insulation factors of the magnet for HTS SMES. And a surface flashover as well as volume breakdown in air and vacuum has been investigated with two kind insulators. Finally, we will discuss applications for the HTS SMES including aging studies on model coils exposed in vacuum at cryogenic temperature.

1. INTRODUCTION

The superconducting magnetic energy storage (SMES) has been studied for power utility application, stabilization and compensation with progress of superconducting technology. SMES Has great advantage: inherently high plant efficient, quick response to charging or discharging power by means of solid state switches, and wide controllability of active or reactive power with gate turn off devices. A large SMES with a 100 km radius was initially proposed for reducing a diurnal peak power demand by the University of Wisconsin directed by Boom and Peterson, because of its higher efficiency compared with pumped hydro, battery, flywheel and other energy storage system. Small or medium scale SMES will be in demand for power system stabilization, load fluctuation compensation and voltage control. Moreover, 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. The commercial application of many HTS magnets, however, requires refrigeration at temperatures below 77 K, in order to take advantage of a greater critical current density of HTS and reduce considerably the size and weight of the system. The magnet is driven in vacuum condition. The need to reduce the size and weight of the system has led to the consideration of the vacuum as insulating media [1].

Thus, for the development of the magnet, cryogenic insulation design should be established to accomplish miniaturization that is a big advantage of HTS SMES. In order to assess the adequacy of the insulation, it is necessary to have some understanding of the breakdown mechanism, especially in vacuum and solids which are normally used in combination. Although our understanding about those is very incomplete, the characteristics or trends were obtained from variety tests using model electrode system. Particularly, the characteristics of surface electrical discharge creep on the surface of a solid insulator in a vacuum must be understood, because the surface electrical discharge on the solid insulator is lower than that without one [2].

In this paper, we present and discuss very fist results in this field, focused on Al_2O_3 and GFRP (glass fiber reinforced plastics). Firstly, we summary the insulation factors of the magnet for HTS SMES. Secondly, we experiment the spacer configure effect in the dielectric flashover characteristics. From the results, we confirm that our research established basic information in the insulation design of the magnet.

2. CONDUCTION-COOLED HTS SMES SYSTEM

2.1. HTS SMES Plant

A conduction-cooled HTS SMES system consists of superconducting magnet and power conversion module of series and parallel topology and many other parts for operation. The basic principle of HTS SMES is to store energy in the magnetic field generated by the DC current flowing through a coiled wire. If the coil were wound using a normal wire such as cooper, the magnetic energy would be dissipated as teat in the wire's resistance. However, if the coil were wound using a HTS wire such as Bi-2223, the energy can be stored in a persistent mode, indefinitely, until required. The coil is a DC device, yet charge and discharge are usually accomplished through an AC utility grid, so that a power conditioning system (PCS) is required as the interface. The PCS can use a standard solid-state DC/AC converter transferring power back and forth between the superconducting coil and the grid/load [3]. Fig. 1 is a generic block diagram showing the major elements of a large-scale conduction-cooled HTS SMES unit operating at 30 K in vacuum.

The HTS magnet is the most important part, which can store electromagnetic energy with out changing the energy to chemical or mechanical. And a power conversion module is also very important. Depending on size and application, the magnet could be a solenoid or a toroid [4]. The magnet is cooled by cryocooler. And it is connected to the PCS through a pair of heat leak reduced leads. Here, a material of joint part that magnet and cryocooler adhere must have high thermal conductivity and high dielectric strength. This point is an very important component of the insulation of magnet both in terms of stability and reliability.

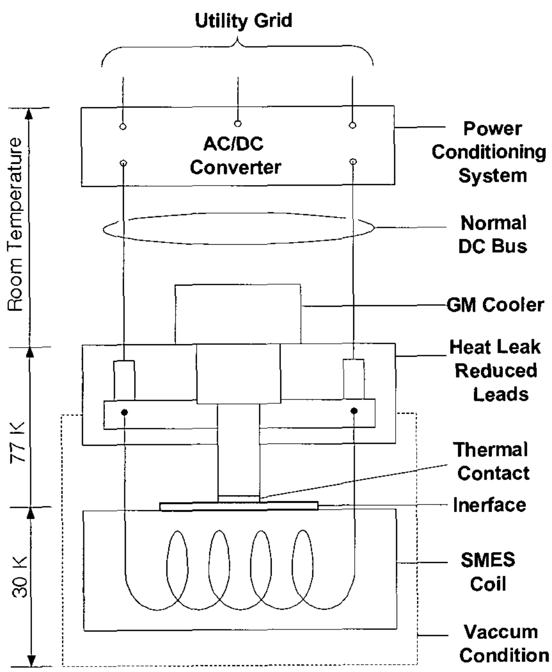


Fig.1. Schematic diagram of a conduction-cooled HTS SMES plant.

2.2. Insulation compositions and materials of the magnet

There are six insulation compositions:

1) Turn-to-turn insulation
2) Layer-to-layer insulation
3) Coil-to-chamber insulation
4) Coil-to-cryocooler insulation
5) Lead-to-flange insulation
6) Lead-to-lead insulation

However, according to the winding form, the insulation components become some different. All compositions are important, practically coil-to-cryocooler, lead-to-flange and lead-to-lead insulation are very important for electrical and thermal insulation of a conduction cooled HTS SMES. These insulations must have thermal and electrical stability at the same time. These insulation techniques are may be very difficult. Because there are a heat and electrical conduction in inverse proportion.

Traditional high voltage insulation of a coil type machine is a composite material consisting of mica paper, impregnating resin and glass fabric [6]. These materials have excellent insulation properties, but with relatively low thermal conductivity. To develop most suitable Coil-to-Cryocooler insulation, we present basic concept of materials for increasing the thermal conductivity and the high voltage insulation. The parameters of such a material are as follows:

-High thermal conductivity
-High electrical insulating capability
-High partial discharge resistance
-High chemical stability and low toxicity
-Availability in constant and high quality
-High compressive stress
-Low rate of transformation
-Low cost

Table 1 shows a compilation of some materials with high thermal conductivity. Based on extensive testing and a cost-benefit analysis, Al_2O_3 material was chosen. And GFRP is used material for support and insulation of machine operating cryogenic temperature extensively. Therefore, GFRP was chosen, too. Table 2 shows main characteristics of the selected materials.

TABLE I
THERMAL CONDUCTIVITY OF INSULATING MATERIALS WITH HIGH DIELECTRIC STRENGTH.

Diamond	2000	W/mK
Sapphire	35	W/mK
BN cubic	1300	W/mK
BN hexagonal	40-120	W/mK
SiC	25-100	W/mK
Si_3N_4	50	W/mK
BeO	370	W/mK
Al_2O_3	25-40	W/mK
AlN	150	W/mK
ZrO_2	3	W/mK
MgO	25-50	W/mK

TABLE II
MAIN CHARACTERISTICS OF THE MATERIALS.

Characteristics	GFRP	Al_2O_3
Density (g/cm^3)	1.7	3.9
Thermal conductivity (W/mK)	0.24	30
Strength (kg/mm^2)	55	24
Resistivity (Ω · cm)	>10^{14}	>10^{14}

3. EXPERIMENTAL PROCEDURES

The investigation of the flashover characteristics of Al_2O_3 and GFRP is carried out in a vacuum chamber at pressure of 2×10^{-5} Torr and at temperature of 320 K and 83 K with ac voltage. Fig. 2 shows the electrode configuration for the experiment. Multi-layer insulation spacer was placed between plane and plane electrodes. The diameter of plane electrode was 40 mm. The electrodes were made of stainless steel. Lower part electrode was contacted to cooling head. And cry-con thermal conductive grease which is made by lake shore was used for heat transfer and electrical cur-off. The electrode system was cooled by the cryocooler after the electrode was set inside. The pressure inside vacuum chamber was fallen to 2×10^{-4} Torr.

The spacer for this experiment is shown in Fig. 3. Two kinds of material were used in this experiment; there are 2 mm thickness GFRP and 1.65 mm thickness Al_2O_3. In determining the flashover characteristics of GFRP and Al_2O_3 Multi-layer, various configurations of spacers with tip and without tip were used. The main characteristics of the specimens were given in Table 1. Fig. 4 shows the vacuum chamber with cryocooler which is made in USA. The vacuum chamber with high voltage bushing and windows was made form stainless steel (200 mm inner diameter and 250 mm long).

The electrical test apparatus were ac dielectric strength test set, which is made of Kyonan Electric CO., LTD (50/60 Hz, 100 kV, 1 kVA). The test samples were subjected to a slow ac ramp (1 kV/s) one by one until breakdown and flashover occurred.

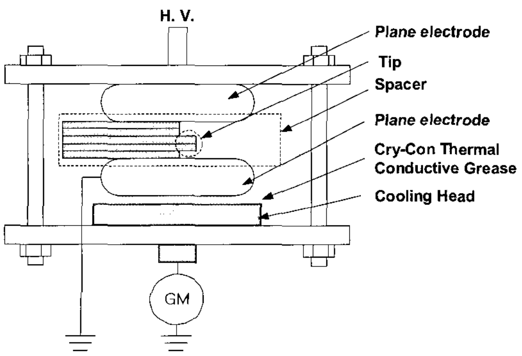


Fig. 2. Electrode configuration.

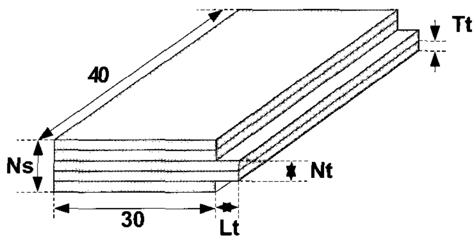


Fig. 3. Spacer for this experiment (unit: mm); 1. Ns: Number of spacer, 2. Lt: Length of tip, 3. Nt: Number of tip, 4, Tt: Thickness of tip.

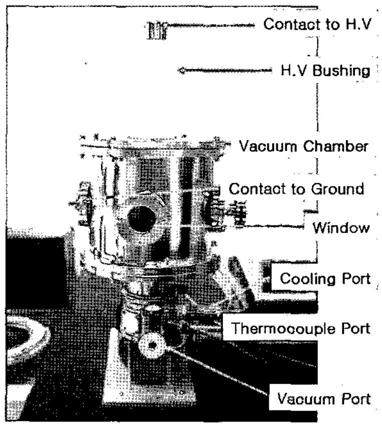


Fig. 4. Setup for experiments.

4. RESULTS AND DISCUSSIONS

The effects of pressure on the breakdown strength of 1.65 and 3.3 mm vacuum gaps were measured under ac voltage. As shown in Fig. 2, the breakdown voltage reaches a maximum value at the pressure of 2×10^{-4} Torr and the breakdown voltage remains constant for vacuum value < 2×10^{-3} Torr.

Fig. 6 (a) and (b) show a breakdown voltage (BDV) as a function of electrode gap for the plane-to-plane gaps with and without spacer in air and vacuum. As shown in Fig. 6, the breakdown voltage generally increased with gap length and the breakdown voltage without spacer produced higher than flashover voltage with spacer. The breakdown voltage in air increases linearly while the breakdown voltage in vacuum shows a non-linear increase. From Fig. 6, we determined the relation ship between breakdown voltage (in kV) without spacer in vacuum (Equation (2)) as well as in air (Equation (1)) and gap length (in mm). The approximated lines are given by

$$BDV=2.06g + 1.82 \quad (1)$$
$$BDV= 15.323g^{0.59} \quad (2)$$

As shown in Fig. 7 (a) and (b), we investigated effects of flashover voltage by tip length (Lt=0, Tt, 2Tt mm) and position of single tip at Lt=2Tt mm. In Fig. 7 (a), the location of the tip is fixed at center. In the case of single tip, the flashover voltage increases with increasing tip length. The length of tip increased to 40 % ((Lt/Ns)×100 %) about surface length, and appeared constantly even if length of tip increase after 40 %. In each of the Fig. 6 (b), Fig. 7 and Fig. 8, the tip of length is fixed at 2Tt mm. When tip is located in center, flashover voltage is higher.

Fig. 8 (a) and (b) show flashover voltage as a function of tip number of the GFRP and Al_2O_3 in air, respectively. According as number of tip increases, flashover voltage become low gradually. According as number of tip increases, surface length of tip increase. Thus, the discharge happens through surface of the tip.

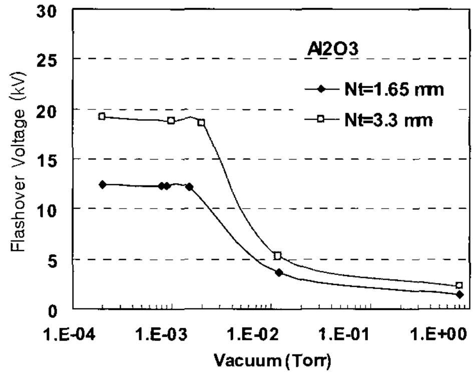
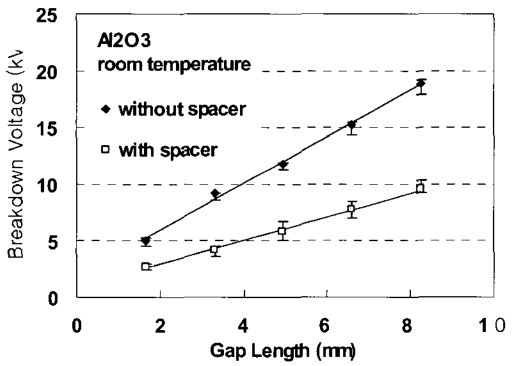
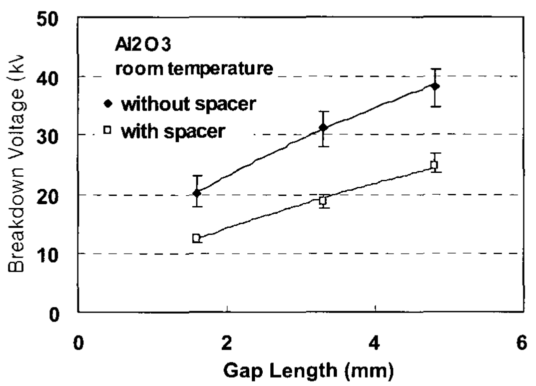


Fig. 5. Effect of pressure.

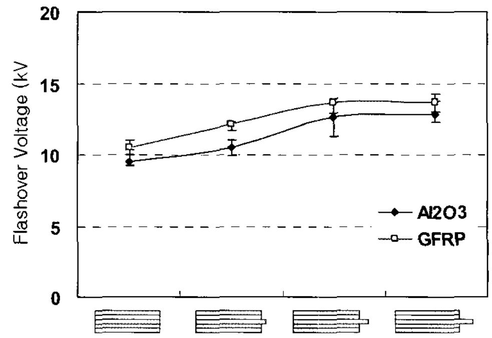


(a) In air

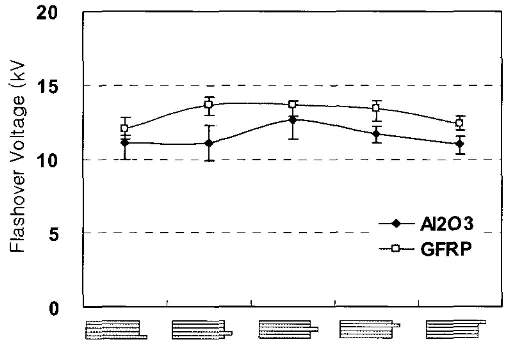


(b) In vacuum

Fig. 6. Breakdown voltage with and without spacer as a function of gap length.

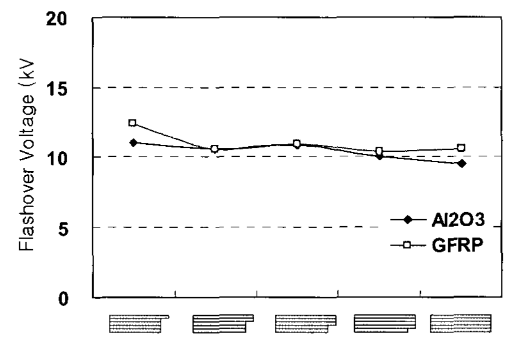


(a) Length effect

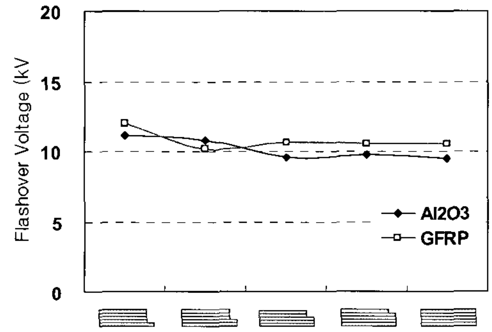


(b) Position effect

Fig. 7. Flashover voltage as a function of tip length and position.



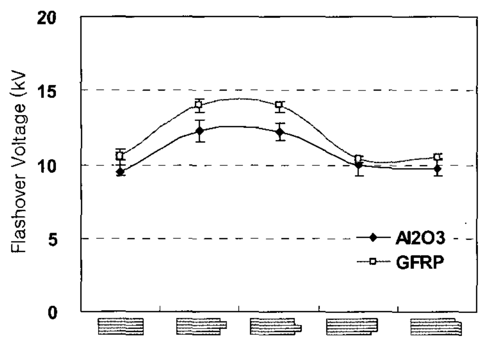
(a) Increase from high voltage



(c) Increase from ground

Fig. 8. Flashover voltage as a function of tip number.

Fig. 9 (a) shows effect of polarity in air on flashover voltage. The result is shown that the effect of polarity is lower than that of tip arrangement. Other researchers have observed little or no difference between room temperature and 100 K for lexan [6].



(a) Polarity effect

Fig. 9. Flashover voltage as a function of polarity and temperature.

5. CONCLUSIONS

In order to observe the flashover phenomenon in air and vacuum, the breakdown and flashover voltage under room and cryogenic temperature were conducted with plane-to-plane electrode after analyzing the insulation compositions of the conduction-cooled HTS SMES.

The breakdown voltage is kept at vacuum value < 2×10^{-3} Torr. The flashover voltage is increased as increasing the gap length and spacer number. A single tip on the spacer acts as a barrier against the electrons and reduces the electric field, thus flashover voltage increases. However, the flashover voltage decreases with increasing tip number. And polarity did not greatly influence in rise of flashover voltage.

ACKNOWLEDGMENT

This work was supported by Electric Power Industry Technology Evaluation & Planning.

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