Superconductivity and Cryogenics
Vol.13, No.2, (2011), pp.17~20

A study on the breakdown probability distribution of materials for conduction-cooled HTS SMES

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Received 4 April 2011; accepted 18 May 2011

***Abstract*-- Superconducting magnetic energy storage (SMES) has attracted a great deal of interest from the viewpoint of energy saving. The magnet of conduction-cooled high temperature superconducting (HTS) SMES is cooled down by a cryocooler. One of the most important problems to be assured the protection of magnet and cryocooler is breakdown at cryogenic temperature. In this study, we investigated insulation materials such as Kapton, Aluminum Nitride (AlN), Alumina (Al_2O_3), glass fiber reinforced plastics (GFRP) and vacuum in cryogenic temperature. Also, we analyzed statistically the Weibull distribution of breakdown voltage.**

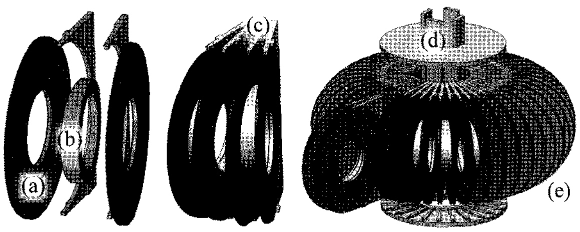

Fig. 1. Insulation composition of the conduction-cooled HTS SMES; (a) turn-to-turn insulation, (b) layer-to-layer insulation, (c) coil-to-coil insulation, (d) cryocooler-to-coil insulation, (e) ground insulation.

1. INTRODUCTION

Recently, superconducting machines such as superconducting cable, transformer, superconducting rotating machines and HTS SMES have attracted a great deal of interest from the view point of energy saving [1, 2]. HTS SMES is one of direct electrical energy storage. The conduction-cooling method for its cooldown is more efficient, small and light. Besides, there is no limitation in terms of the installation spot and angle, and flexible composition is possible [3, 4]. One of the most important and difficult problems to be solved to assure the high reliability and long life of such a machine is a breakdown at cryogenic temperatures [3, 4]. Especially, the cryocoo- ler in conduction-cooled HTS SMES must be protected from the high voltage [3-5].

The conduction-cooled HTS SMES system is consisted of various insulation compositions. Fig.1 shows the insulation compositions of the conduction-cooled HTS SMES. Pancake coil modules stand perpendicularly to the central axis direction and arranged in a donut shape. Major insulation elements are comprised of turn-to-turn insulation (a), layer-to-layer insulation (b), coil-to-coil insulation (c), cryocooler-to-coil insulation (d), and ground insulation (e).

The design factor of turn-to-turn, cryocooler-to-coil and ground insulation is the puncture breakdown properties to the insulation thickness of the insulating materials and vacuum. For that of layer-to-layer and coil-to-coil insulation is the creeping discharge properties of insulating materials in vacuum. The bobbin of conduction-cooled SMES made metallic materials for the efficiency of thermal conduction. If the double pancake coils have a breakdown, the electrical current may flow to the bobbin that is contacted with cryocooler of ground potential. So spacers between coils have not creeping discharge from a coil to another coil.

Many researchers have been investigated for the dielectric properties under high voltage and cryogenic temperature conditions. However, the useful data for practical insulation design have not been obtained enough. Thus, to achieve the most suitable insulation design for the HTS SMES, it is important to evaluate breakdown voltage for insulation factors. Also, it is important to analyze statistically the data using Weibull distribution.

In this paper, we will report on the Weibull statistic of breakdown voltage for conduction-cooled HTS SMES.

2. EXPERIMENTAL

Fig. 2 shows an experimental apparatus. It is comprised of a voltage supplier, electrode system, cryocooler and vacuum device. The cryostat is made of stainless steel whose inner height and diameter is 600 mm and 300 mm, respectively. To prevent the penetration of heat, the vacuum thermal insulation layer is used.

A Gifford-McMahon cryocooler (AL300, Cryomech Co. Ltd.) of single-stage has cooling capacity of 200 W at 50 K.

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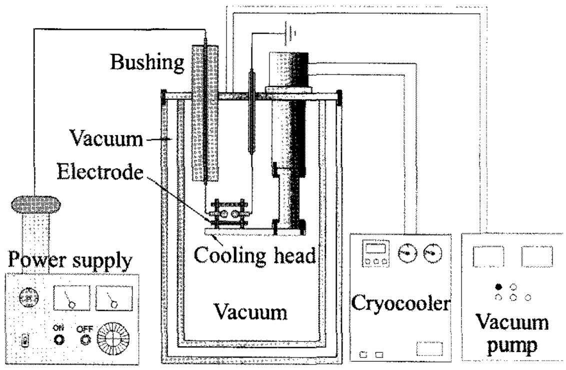

Fig. 2. Experimental apparatus.

The maximum cooling temperature with no load is 25 K.

A DC voltage (max. 100 kV) was applied between the electrodes. 10 times breakdown voltages were measured at each given condition. The maximum probability voltage is obtained from 0.1% value of Weibull distribution.

Fig. 3 (a) shows the electrode system for turn to turn insulation. Kapton tapes of 0.025 mm thickness and 10 mm width were wound on a copper wire. And wrapping number on the copper is 1, 2 and 3. The overlapping rate is 30%. Two insulated wires were joined, and high voltage and grounding were connected to each opposite side.

Fig. 3 (b) shows the electrode system for flashover discharge. The electrodes were made with stainless steel tape. The lower specimen was contacted to cooling head of cryocooler. A tip angle of the triangular electrode is 60° and tip radius is 0.025 mm. The plane electrode has 30 mm in width. And its corner has a radius of curvature of 10 mm to prevent the concentration of electric field at edge.

Fig. 3 (c) and (d) show the electrode system for puncture breakdown. The electrodes were made with stainless steel sphere and plane. Insulating materials such as coated Al_2O_3 and vacuum were placed between sphere and plane electrode. A radius of sphere electrode is 6 mm. A plane electrode is 20 mm in height and 40 mm in diameter.

The electrodes were polished with paste and washed by ultrasonic cleaner in ethanol. It was set to the cooling-head of cryocooler and cooled by the cryocooler. The electrode temperature was measured using a silicon diode attached to the cooling plate. When the cooling head cooled down to 45 K by conduction-cooling method and vacuum pressure attain to 2×10^{-6} torr, DC voltage is applied by manual and rising rate is 2 kV/sec.

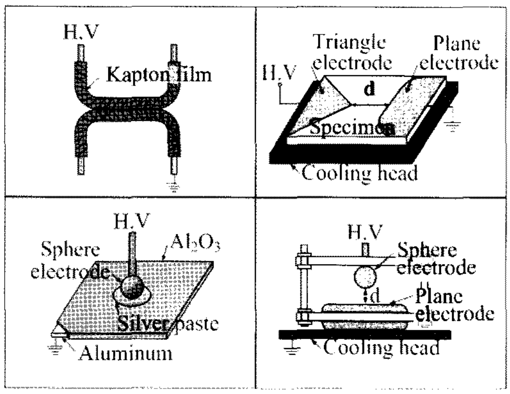

Fig. 3. Electrode systems; (a) for turn-to-turn insulation, (b) for flashover discharge, (c) for puncture breakdown of Al_2O_3, (d) for puncture breakdown of vacuum.

3. RESULTS AND DISCUSSION

3.1. Kapton for turn-to-turn insulation

Fig. 4 shows the Weibull probability distribution of the breakdown voltage with Kapton film. Weibull distribution is generally using for the electrical breakdown strength E. When compared with the normal distribution, Weibull distribution has zero probability at the $E \leq E_{min}$ and its density distribution is not bilateral symmetry [6].

In the figure, shape parameter (Shape), scale parameter (Scale) and experimental number (N) of each layer count are indicated. The electrical breakdown voltage of the point with the 0.1% of probability is referred to as the maximum breakdown strength. The insulation thickness of the Kapton is determined with the ratio of maximum electrical breakdown strength. Also, the probability P of the Weibull distribution for the electric field strength E is given by

$$P = 1 - \exp\left[-\left(\frac{E - E_{min}}{E_0}\right)^m\right], \quad (E \geq E_{min}) \qquad (1)$$

$$= 0 \qquad , (E \leq E_{min}) \qquad (2)$$

Here, E_{min} refers location parameter, E_0 to scale parameter, m to shape parameter. Based on E_{min} value obtained from extensive data of repeated tests, insulation thickness is designed [7], [8].

Table I lists Weibull shape parameter m and scale parameter E_l estimated from the slope of Weibull plots for each layer number in Fig. 4. This table shows that the scale

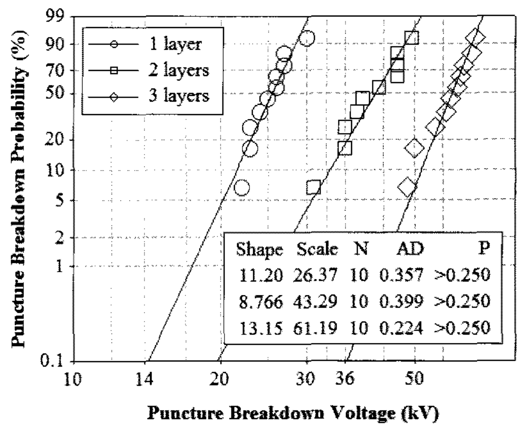

Fig. 4. The Weibull probability distribution of the puncture breakdown voltage according to the Kapton winding number.

TABLE I
WEIBULL SHAPE PARAMETERS AND SCALE PARAMETER.

turn-to-turn electrode (30% overlapping)				
source	wrapping number (layer)	thickness (mm)	E_l (kV/mm)	m
DC	1	0.1	26.37	11.20
	2	0.2	43.29	8.766
	3	0.3	61.19	13.15

parameter E_l increased according as layer number is increased. For example, E_l increased from 26.37 to 61.19 kV/mm according as the layer number increased from 1 layer to 3 layers. The breakdown voltage increases with the number of windings. Also, the maximum breakdown voltage is 14, 20 and 36 kV, respectively. The maximum operation voltage of general HTS SMES is less than DC 10 kV. Therefore, Kapton wrapping for turn to turn insulation is enough 1 layer of 0.025 mm thickness and 10mm width with 30% overlapping. However, the thickness of Kapton film is very thin. To avoid the mechanical damage of film, it is desirable to wind 50% overlapped.

3.2. GFRP for layer-to-layer and coil-to-coil insulation

The material for layer-to-layer insulation must have excellent electrical insulation and mechanical properties at the cryogenic temperature. In this study, we choose the GFRP that it is used material for pancake bobbin and spacer.

Fig. 5 shows the Weibull probability distribution of surface flashover voltage with GFRP. As evident from this figure, the DC flashover voltage increases with electrode distance of GFRP.

3.3. Ceramic for cryocooler-to-coil insulation

The cryocooler of HTS SMES is very expensive. Therefore, the cryocooler-to-magnet insulation is the most important insulation element in a conduction-cooled SMES. AlN ceramic insulator with excellent thermal conductivity (150 W/mK) is inserted between the cooling head and magnet bobbin [9].

Fig. 6 shows the Weibull probability distribution of discharge characteristics of AlN. The surface flashover is represented by ◇, and puncture breakdown strength is represented by ○, respectively. The surface distance between electrodes is 6 mm and AlN thickness is 1 mm. As can be seen in the figure, the surface flashover and the puncture breakdown 0.1% Weibull maximum breakdown probability strength is 4.55 and 39.38 kV/mm respectively. Since the cooling head and magnet bobbin should be contacted with high pressure for conduction-cooling, it is thought that insulation only through the thin AlN plate would be not unsatisfactory. Therefore, this study applies the insulation method in line with another appropriate cooling system.

Fig. 7 shows the Weibull probability distribution of the puncture breakdown according to Al_2O_3 thickness. The oxidizing thickness of Al_2O_3 by anodizing method was 0.025, 0.040, 0.60 and 0.066 mm. The breakdown voltage

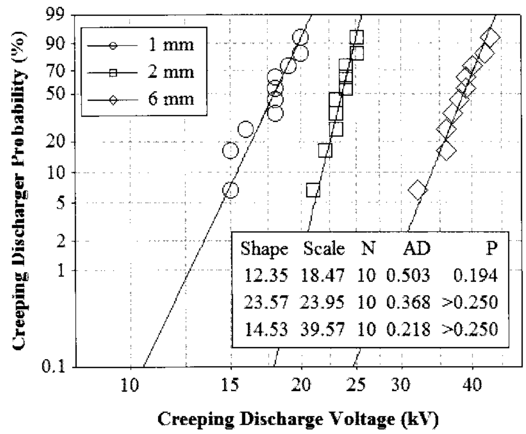

Fig. 5. Weibull probability distribution of surface flashover voltage according to the GFRP creeping distance.

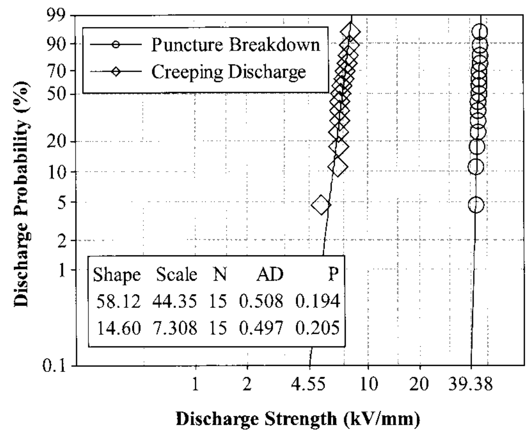

Fig. 6. Weibull probability distribution of the discharge characteristics with AlN plate.

increases with the thickness of AlN plate. Besides, the uncertainties in breakdown voltage are very big than the AlN plate. Especially, in case of 0.025 mm, average breakdown voltage is 2 kV, while its minimum voltage and maximum voltage are 1 kV and 3 kV respectively, showing a ±50% difference. It is considered that the error in experimental results is due to the thickness error in fabrication process of Al_2O_3 coating. The errors of Al_2O_3 coating thickness were expected about ±30% of demanded thickness.

3.4. Vacuum for ground-to-coil insulation

Ground insulation is the element between a cryostat and inner devices such as magnet coil, cryocooler and current lead. The inside of the cryostat is operated a vacuum condition for insulation and cooling. In this experiment, the breakdown properties of a vacuum were investigated at 40 K and 10^{-6} torr.

Fig. 8 shows the Weibull probability distribution of breakdown characteristics in the vacuum condition. As shown in the figure, the breakdown strength of the vacuum is excellent. The maximum voltage is 28.6 kV when the

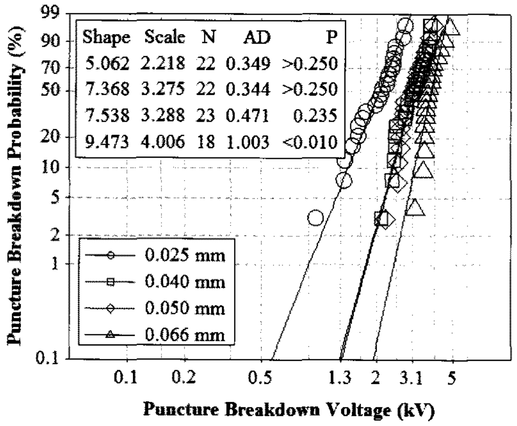

Fig. 7. Weibull probability distribution of the puncture breakdown with Al_2O_3.

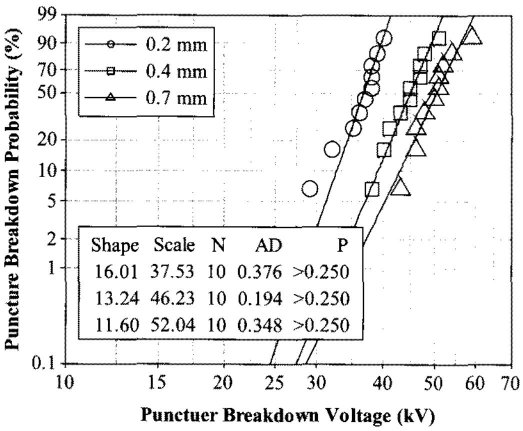

Fig. 8. Weibull probability distribution of the puncture breakdown according to gap distance of vacuum.

electrode distance is 0.7 mm. As the operating voltage of HTS SMES, the insulation distance between that is very short length. However, it should be noted that this value is based on the quantitative calculation. Actually, it must be determined considering the allowance of the mechanical properties such as shocks and oscillations of a cryostat.

4. CONCLUSION

This study presents the major insulation elements of conduction-cooled HTS SMES. The discharge properties of each insulation element were classified into turn-to-turn insulation, layer-to-layer insulation, cryocooler-to-coil insulation and ground insulation.

The discharge characteristics of insulation materials such as Kapton, GFRP, Al_2O_3 and vacuum for each element were investigated. The measured results were used to calculate the 0.1% maximum probability through Weibull distribution by the statistic processing.

In the future, as for the HTS SMES insulation, not only the electric characteristics but also the mechanic characteristics and thermal characteristics should be considered in the comparison examination of the insulation characteristics. In this regard, the magnet model production and test-based verification project are under contemplation.

ACKNOWLEDGMENT

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

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