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Breakdown Characteristics for Insulation Design of HTS Transformer in Liquid Nitrogen

J.M. Joung, S.M. Baek, S.H. Kim
Electrical material lab., Department of Electrical Engineering, Gyeongsang National University and Automation and Computer Research Centre of Engineering Research Institute,
Jinju 660-701, Republic of Korea

shkim@nongae.gsnu.ac.kr

***Abstract*—HTS transformer is promising one of HTS power applications to be commercialized in the near future. To realize the applications, insulation technology in the coolant, liquid nitrogen, should be established. So breakdown characteristics should be considered at insulation components; turn-to-turn, layer-to-layer, winding-to-winding, were investigated. Firstly breakdown strengths of Kapton films were compared with Kraft paper these are as turn insulator. And next the characteristics of surface flashover on FRP were measured and the influence on breakdown strength of bubble generated with joule heat was discussed with the shape of cooling channel between layers. Finally barrier effect at winding-to-winding was discussed.**

1. INSTRODUCTION

More and more, the development feasibility of the High Temperature Supercoducting (HTS) application to the power apparatus has been growing up thanks to the development of long length HTS tape having high critical current and good mechanical characteristics. The power applications; HTS cable, HTS transformer, HTS fault current limiter, etc, are expected to be made in the near future and then the applications will solve the energy problems with transporting high capacity of energy efficiently and steadily to the consumers [1-3].

One of the goals of the "Applied Superconductivity Technology of the 21st Century Frontier R&D Program" during the 1st phase (2001~2003) is the development 1MVA 22.9kV single phase HTS transformer. The transformer will be made of a series of double pancake-coils. For the development of the transformer, it is necessary to establish the insulation technology in LN_2 [4-6]. However, the breakdown mechanism in LN_2 was not understood enough. Also the dielectric database is poor, so much effort needs to gather and understand the characteristics through various experimental investigations. Most of all, the investigation about insulation components of HTS transformer should be distinguished and the breakdown characteristics at the each location should be considered.

2. INSULATION COMPONENTS

In detail, the insulation components inside of the transformer windings consist of three parts as like turn-to-turn, layer-to-layer, winding-to-winding mainly.

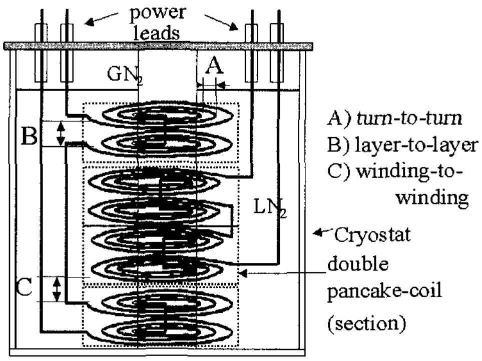


Fig. 1. The insulation components of the HTS transformer.

They are described at the figure 1.

In particular, the characteristics of flashover creeping on the surface of a solid insulator in a coolant must be understood because the surface flashover strength is lower than without the solid dielectrics that bridges electrode gap between layers. However, amount of spacers should be placed as an insulator, a cooling channel and a supporter of structures. And it is well known that the introduction of a thin insulator between windings in oil gaps significantly raise the dielectric strength of the system [7,8]. This benefit effect of insulating barrier is widely used in the designing and dimensioning of the insulating structure especially in power transformers. So the barrier effect in LN_2 must be understood.

In addition, performance of LN_2 may be affected easily with bubbles, contaminant particle, electrode surface condition, field configuration, etc. For that reason, amount of study on the influence of bubbles on the dielectric characteristic have been carried out [9,10]. In the practical insulation system of power equipments, the characteristic of cooling channel should be taken into account how the cooling channel withdraw the bubbles well.

From this viewpoint, firstly the dielectric strength of Kapton film which is now promising for turn to turn insulation was tested. And next characteristics of surface flashover with electrode arranging types were discussed and the influence on breakdown strength of bubble generated by joule heat was discussed with the shape of cooling channel between layers. Finally the barrier effect in liquid nitrogen between windings as a function of the barrier position was discussed.

3. EXPERIMENTAL SET-UP

Figure 2 shows the schematic draw of experimental set-up. The experiment apparatus consists of a cryostat, a high voltage power supply, an electrode system and so on.

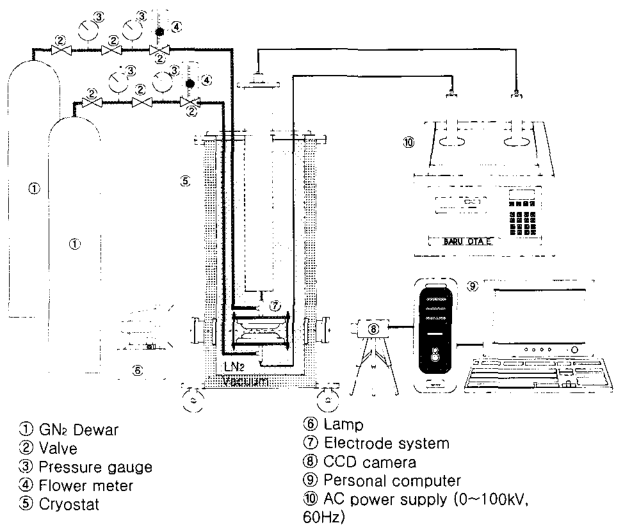


Fig. 2. Schematic of experimental set-up.

The cryostat was made of two dewar flasks; inner one is for test and outer one is for thermal stability. The dewars were painted with silver for blocking up radiant heat and have observation windows. Through the windows flashover phenomena were observed.

The capacity of the power supply is AC 90kV, 300VA. The high voltage was applied to electrode and increased at the rate of 1kV/s until flashover. The data averaged after more 10 tests and marked on graphs.

There are 4 kinds of the electrode systems used for the tests. A silver (Ag) electrode used each tests shaped the HTS tape. The Ag tape is 0.2mm in thickness and 3mm in width. Aluminum electrode used for surface flashover test is 0.11mm in thickness. Needle electrode for barrier effect is 18° and 17μm in tip angle and tip radius. The schematic of electrode system will be showed at each result graph.

4. RESULATS AND DISCUSSION

There are two types of Kapton films. One has an adhesive side and the other does not have. The breakdown strengths of the films are compared with Kraft paper in figure 3. The Kraft paper is used widely for convention transformer. Ag tape was used for the electrodes. The samples were inserted between Ag electrodes. The films were wide enough not to occur surface flashover. Karft paper, adhesive Kapton tape (Kapton 1) and Kapton film (Kapton 2) are 0.15mm. 0.13mm.and 0.14mm in thickness respectively. Figure 3 also shows the schematic of electrode system.

In the figure the breakdown voltage of Kapton films are higher than Kraft paper and the voltage of Kapton 2 is higher than Kapton 1. Although the thickness of Kapton 1 and 2 are similar the breakdown strength of 1 is less than Kapton 2. It is considered that a frozen adhesive make some crack in the insulator result from the difference of the contractions.

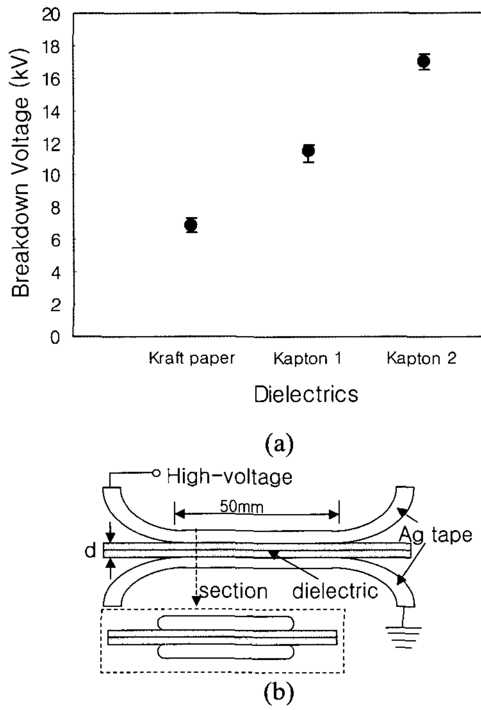


Fig. 3. (a) breakdown characteristics of the turn insulators and (b) schematic of electrode system.

Figure 4 shows the surface flashover characteristics tested as function of surface length. The electrode systems used in the experiment arranged in parallel with electrode 1 and 2 depicted in the figure and in vertical with electrode 1 and 3. The thin aluminum electrodes are shaped in a right triangle (electrode 1) and a rectangle (electrode 2 and 3). In detail, the size of rectangle is 48mm of width and 20mm of height. The back electrode (4) is placed at the counter side of the FRP. The characteristics of vertical electrode are marked with circle and the parallel are marked with square colored black. The lines of with white square shows the characteristics with back-electrode consisted of electrodes1, 2 and 4. Surface length is the distance between electrodes. In the surface length of the vertical can be scaled like that (L-t)/2. The scaled length is so-called as collar length.

The figure shows that the flashover strength with back-electrode is worst of all and the strength is improved with thickness more than with surface length in the vertical arrangement. Explaining this with the surface capacitance that makes easy to flashover because it may

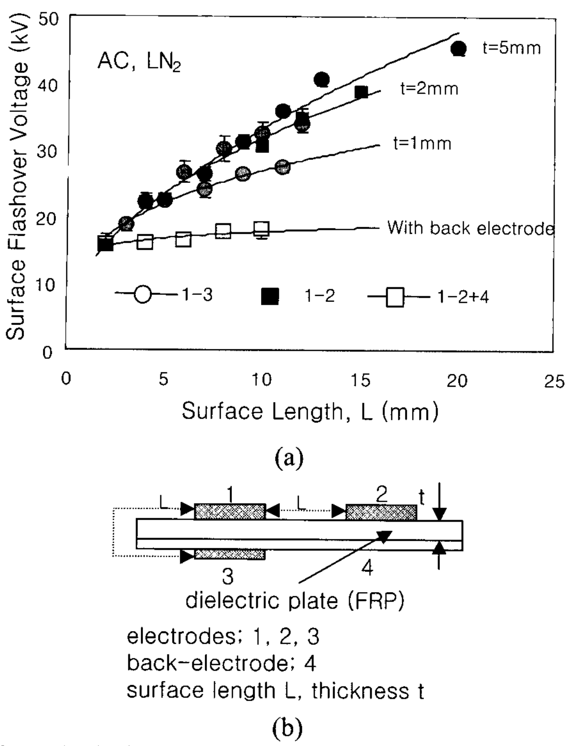


Fig. 4. (a) the flashover characteristics depending on surface length and (b) schematic of electrode system.

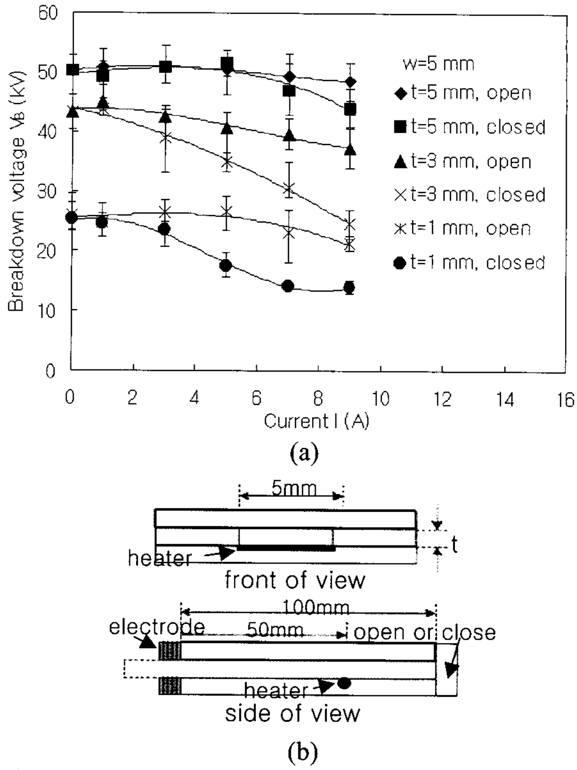


Fig. 5. (a) the effects of a cooling channel to the breakdown with increasing the heater current and (b) schematic of electrode system.

have much space charge, the longer collar of spacer increases the capacitance. On the other hand the thicker spacer decreases that.

In the cases the back-electrode locate counter side and the electrodes are laid by vertical, the components of electric flux lines of perpendicular with the surface of dielectric plate increase and the field working on micro gap between electrodes and FRP plate also enlarges. For that reason, the characteristic with back electrode is worst and the flashover voltages are more increased with the thickness.

In order to know the effect of a cooling channel to the breakdown of LN_2 when bubbles are generated by joule heat, series of tests were conducted as a function of the channel size and current of heater. The width and length of cooling channel are 5 and 100 mm respectively at constant and the thickness changed at each test are 1, 3 and 5 mm. In the middle of the length of the cooling channel a heater is placed and Ag electrodes locate on one side of the channel. The other side of the cooling channel can be close or open. The electrode system is showed in figure 5.

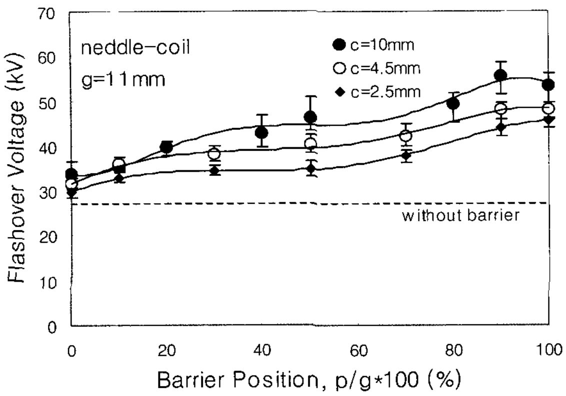
Figure 5 also shows the results. The breakdown voltages are decreased with increasing heat current in all graphs. The decline of the voltages is reduced with increasing channel thickness t and much more when the cooling channel is open.

It is well known that the bubbles are harmful to the dielectric strength. Especially in the case of a closed channel, bubbles are captured cooling channel and bridges electrodes easily. However, in the case of an open channel, bubbles were exhausted well through the open channel. Thus, the bubbles do not influence much the breakdown voltage. When t=5 and the channel was open, it was considered that is the minimum size for withdrawing bubbles well at the given width.

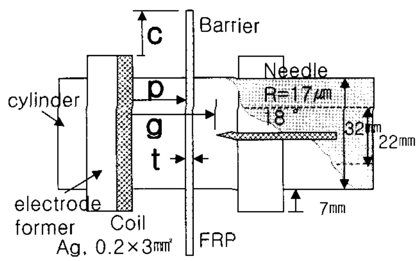
If we assumed that HTS tape has 200A of operating current at 4 parallel conductor, 0.3 Ag ratio, 0.3×4.3 ㎟ of cross sectional and Ag sheath, and that the tape is quenched partially along 5mm length, the heat power is calculated about 0.2watt with passing the all current to Ag sheath. As the power of the heater is measured 1.36watt at 9A it would be sufficient to determine the size of cooling channel.

The barrier effect tests were conducted with coil-needle system in liquid nitrogen with FRP barrier. Figure 6 shows the electrode systems. The coil that is one turn of Ag tape and needle are placed on FRP electrode formers of which outer and inner diameter is 46mm, 32mm respectively. And then the electrodes are assembled with FRP cylinder that is measured 32mm and 22mm in outer and inner diameter. The barrier is located between the electrodes. The letters of c, p, g, t mean collar length, position of barrier, electrode gap and barrier thickness respectively. What p is 0mm and 10mm mean the barrier locates at the side of the coil and needle electrode. The sample is replaced when it is aged with flashover.

Figure 6 shows the flashover characteristic as function of barrier position when each collar length c are 2.5, 4.5, 10mm and the thickness of the barrier is 1mm. It is evident



(a)



(b)

Fig. 6. (a) the results of barrier position relation to the flashover voltage and (b) schematic of electrode system.

that the flashover voltage increase as the barrier is more close to the needle electrode. The voltage increased up to 1.8 times to the flashover voltage of without barrier when g is 11mm and the flashover voltage is increased depending on the collar length c because the flashover occurs detouring the outer of the barrier.

In detail the tendency in the figure 6 can be distinguished into three parts; the region of an increase, the fixed value region and the region having the maximum barrier effect. According to an observation of the flashover phenomena, in the case of both regions close to coil and needle electrode, the flashover occurred after heavy partial discharge and in the case of the fixed region, in the middle of the electrodes, there wasn't partial discharge. Hence, it can be considered that the charge formed as a result of partial discharge was distributed on a surface of the barrier and it stabilized the electric field. However, in the first region, it is assumed that the difference of electric field stabilized with barrier is not big because the electric field at the coil electrode is relatively uniform compared to the sharp needle. Moreover, a probability of existence faults that are harmful to the strength is high because the area partial discharging is wider than that of the needle. So, in the first reason the barrier effect is low. On the contrary, it is considered the interruption activity of the propagation of discharge leaders mainly acts in the second region so the flashover voltage is almost constant.

5. CONCLUSION

Electrical investigation for the insulation design of HTS transformer was carried out The insulation component of the HTS transformer was distinguished by turn-to-turn, layer-to-layer, winding-to-winding mainly. And then the breakdown characteristics should be considered at each part such as breakdown of turn insulator, surface flashover and cooling channel between layers and barrier effect between windings were conducted. The results are summarized in followings.

1) For the insulation of the turn-to-turn the commercial Kapton tape was tested. Breakdown voltage of Kraft is 6.89kV/0.15mm, adhesive Kapton tape is 11.5kV/0.13mm and Kapton film is 17.3kV/0.14mm.

2) In the cases the back-electrode locates and the electrodes is laid by vertical, the surface flashover voltage decreased more than the parallel arrangement because the components of electric flux lines of perpendicular with the surface of dielectric plate increase and the field working on micro also enlarge.

3) In the vertical arrangement of the electrode, it is more effective to increase of the thickness than to increase collar length.

4) When the cooling channel is closed, the breakdown voltage dropped much with bubbles captured inside of cooling channel. However, in the case of open channel with 5mm in width and thickness, the breakdown voltage was almost fixed because the bubbles are withdrawn well. The cooling channel should be designed to exhaust bubbles well.

5) As the barrier is near the needle electrode, the flashover voltage was increased to about 1.5 times. This results due to the effect that the barrier stabilizes the electric field and interrupts the propagation of discharge streamer.

ACKNOWLEDGMENT

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