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AC Breakdown Characteristics of Nomex and Kapton as Insulation Material Used in Pancake Tape Coil Structure for Resistive-Type Superconducting Fault Current Limiter

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Abstract

A resistive-type superconducting fault current limiter (SFCL) is one of the most promising superconducting devices in an electrical power system. However, an SFCL has the very obvious disadvantage of a large space requirement when applied in high-voltage-level power networks. Considering the space utilization efficiency, a pancake structure in which superconducting tapes are wound into coils should be adopted. When certain faults occur in a power grid, a relatively high voltage difference will be present in the tape coil. The inner and outer layers are in direct contact; therefore, special measures have to be carried out to overcome high-voltage insulation safety issues. Two commonly used materials are considered in this study: Nomex and Kapton. The basic AC breakdown characteristics in air and liquid nitrogen are explored. A new breakdown-strength testing platform is manufactured to obtain the breakdown voltage. Considering that the edges of the superconducting tape are very thin, the impact of the superconducting-tape thickness on the breakdown strength is explored. Two methods, parallel and vertical lapping, are used to lap the insulation layer onto the tape and are subsequently compared. Finally, a face-to-face electrode structure breakdown test is conducted to simulate the actual working conditions in a tape coil. The results obtained can be used to design and optimize the geometrical structure of the SFCL pancake component.

Keywords: SFCL, Pancake component, tape coil, breakdown characteristic, insulation material, lapping method

1. Introduction

The discovery of high-temperature superconductivity has raised a great deal of interest in the exploration of its potential applications in a power system. A resistive-type superconducting fault current limiter (SFCL) is regarded to be one of the most promising superconducting applications. Resistive-type SFCLs have attracted significant attention, and many related studies have been carried out worldwide (Hassenzahl, 2000). In our university, a 10-kV resistive-type SFCL has been built and tested (Hong et al., 2012). In 2014, a higher voltage prototype will be designed and demonstrated. Different types of primal designs have been reported. Among them, a design using a stack of pancake components (Hobl et al., 2013) has the best performance for space utilization efficiency. In each component, superconducting tapes are wound into a coil. A relatively high voltage difference will be present between two adjacent layers during faults in power system. Special measures have to be taken to overcome high-voltage issues. Lapping an insulation layer around the tape is one possible solution. Therefore, the selection of insulation materials, lapping methods, and other aspects should be studied. The breakdown characteristics of different polymer materials has been tested (Ombello et al., 2002). Further, the insulation properties have been explored at room temperature (Ul Haq, & Raju, 2006) and cryogenic temperatures (Zhang, Zhang, Tan, Luo, & Tu, 2012). A comparison between the DC and AC breakdown characteristics has also been carried out (Seong, Seo, Hwang, & Lee, 2012). The results obtained from all of these tests are valuable and comprehensive. However, all of these former studies have used a standard electrode configuration. No research has considered the actual electrode structure in a pancake component used in an SFCL.

In this paper, we consider Nomex (polyamide) and Kapton (polyimide), which are very commonly used insulation materials and have very good mechanical and dielectric properties in liquid nitrogen (LN2). Tests are conducted to measure the AC breakdown characteristics of these two materials in LN2 and to verify the effectiveness of our newly created test platform.

The fact that a superconducting tape is very thin may undermine the breakdown strength. Furthermore, a very sharp edge will aggravate a partial discharge, and more initial electrons are injected into the dielectric. The use of copper (0.1-mm thickness) and superconducting (0.3-mm thickness) tapes as a comparison will provide further details regarding this issue.

There are two main methods to lap the insulation layer onto the tape: parallel lapping and vertical lapping. In this research, we will demonstrate how these two methods work, and the breakdown characteristics of these two methods will be compared. The results show that vertical lapping can enhance the breakdown strength. Furthermore, a face-to-face electrode structure breakdown test is conducted to simulate the actual working conditions in a tape coil.

2. Experimental Setup

The pancake-structure resistive-type SFCL has been conceptually designed, and a schematic diagram of one component is shown in Figure 1. A layer of insulation material is lapped around the tape.

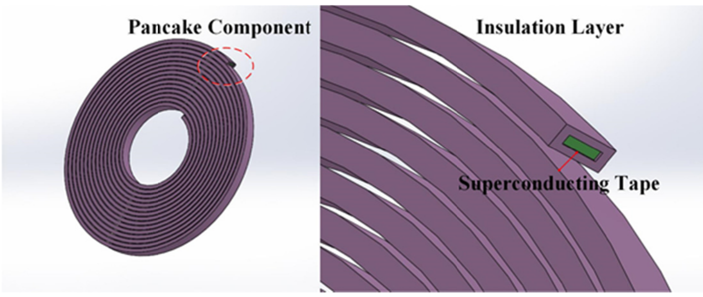

Figure 1. Schematic diagram of one pancake component

The breakdown tests used a 50-Hz AC power source. Nomex and Kapton sheets were prepared and designed to have dimensions of 70 × 70 mm2. The sheets were cleaned with alcohol and placed in air or LN2 environments for 24 h before each test.

A schematic diagram of the experimental setup is shown in Figure 2. This setup is used for performing breakdown experiments and is modified from the previous setup (Li et al., 2014). The double-layered glass vessel has a vacuum between the two layers. In order to prevent the occurrence of bubbles in the LN2 from affecting the experimental results, there is a 10-min interval time between every two experiments. The supporting structure is made of glass-fiber-reinforced plastic (G10) because of its perfect electrical and mechanical robustness. In addition, an AC voltage is applied, increased by 200 V at a time, and maintained for 30 s to observe the occurrence of any breakdown. The initial voltage is set to be 40% of the expected breakdown voltage. If breakdown occurs within six increases in voltage, the initial voltage is lowered, and the test is performed again. For each sample, tests are performed five times, and the average value is used to calculate the breakdown strength.

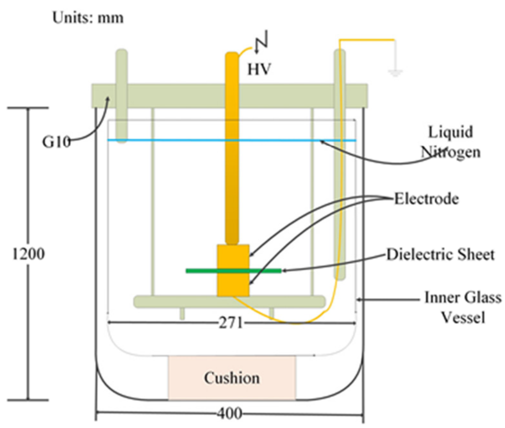

Figure 2. Experimental setup for the dielectric-sheet breakdown test

2.1 Dielectric-Sheet Breakdown Test

A newly fabricated electrode configuration and the entire experimental structure are shown in Figure 3 (a). The configuration of electrode conforms to the IEC 60243 standard, and all metal parts are made of brass. The high-voltage and ground electrodes are 25 mm in diameter and height and have 3-mm rounded edges. Different sample thicknesses are prepared: 0.05, 0.08, and 0.13 mm for Nomex; and 0.03, 0.05, and 0.07 mm for Kapton. Tests are conducted in air and LN2 to make a comparison.

2.2 Influence of the Thickness of the Tape on the Breakdown Strength

Another set of electrodes is fabricated according to the IEC60243 standard. The high-voltage electrode is 6 mm in diameter and 25 mm in height and has 1-mm rounded edges. Superconducting (100 mm in length, 12 mm in width, and 0.3 mm in thickness) and copper (100 mm in length, 12 mm in width, and 0.1 mm in thickness) tapes are used as the ground electrode. The tapes are pressed beneath a metal slug connected to the ground wire. The entire experimental structure is shown in Figure 3 (b). The parallel lapping method is adopted, and the tapes are lapped with Nomex (0.13 mm in thickness) and Kapton (0.07 mm in thickness).

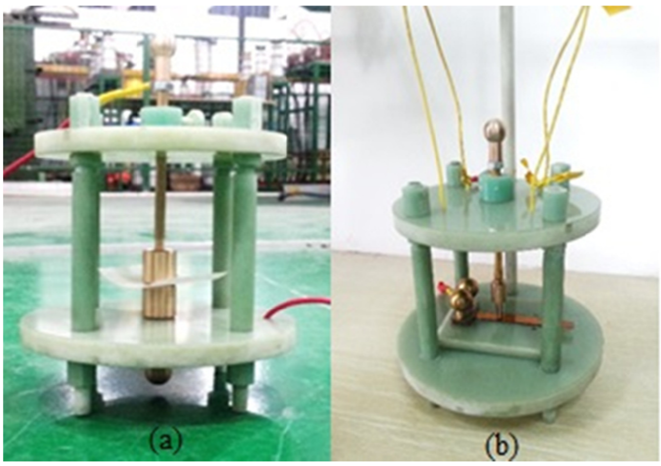

Figure. 3 Electrode configuration: (a) dielectric-sheet breakdown test and (b) the use of copper and superconducting tapes as the ground electrode

2.3 Comparison Between Parallel Lapping and Vertical Lapping

The parallel and vertical lapping methods are shown in Figure 4. The results acquired are compared to explore the differences between these two lapping methods.

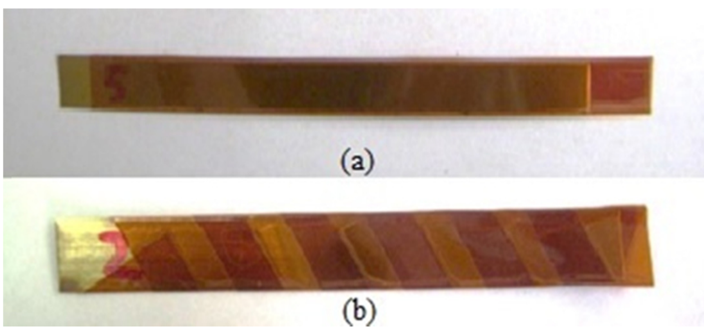

Figure 4. Demonstration of the lapping method: (a) parallel lapping and (b) vertical lapping

2.4 Face-to-Face Electrode Breakdown Test

To simulate the actual working conditions in the tape coil, superconducting tape is used as both a high-voltage electrode and a ground electrode. The electrode configuration is shown in Figure 5. The entire experimental setup is immersed in LN2 in a foam plastic tank. The high-voltage and ground electrodes are lapped with Nomex and Kapton insulation layers, respectively, using the parallel lapping method. It should be pointed out that there are two layers of insulation material between the high-voltage and ground electrodes.

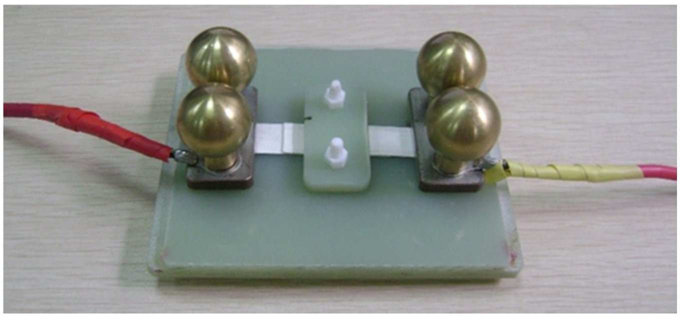

Figure 5. Face-to-face electrode configuration

3. Results and Discussion

3.1 Dielectric-Sheet Breakdown Test

Figure 6 and Figure 7 shows the relationship between the breakdown strength and the thickness of the Nomex or Kapton sheets in air and LN2. The breakdown strength is calculated as the breakdown voltage divided by the thickness. In air, the breakdown strength of Nomex increases as the sheet thickness increases. In contrast, the breakdown strength of Kapton decreases as the sheet thickness increases, and the breakdown strength tends to saturate at 91.4 kV/mm. The breakdown strength of Kapton is almost three times that of Nomex. In LN2, the breakdown strength of both Nomex and Kapton decrease as the sheet thickness increases. The breakdown strengths tend to saturate at 56 and 116 kV/mm for Nomex and Kapton, respectively, and the breakdown strength of Kapton is only two times that of Nomex. Furthermore, Kapton has better dielectric properties than Nomex in both air and LN2. Comparing with the values in air, the breakdown strength of Nomex is increased by at least two times but only 27% for Kapton. This result may mean that LN2 has permeated into the Nomex sheet and significantly enhanced its dielectric strength. This phenomenon is called the complex insulation effect (Zhang, Zhang, Tan, Luo, & Tu, 2012) and is used in transformer insulation by a combination of solid sheets and oil; however, it has not been demonstrated for LN2.

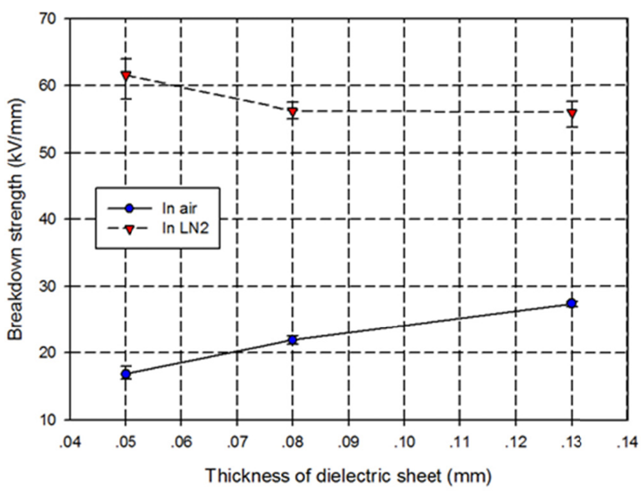

Figure 6. Relationship between the breakdown strength and the thickness of the Nomex sheet

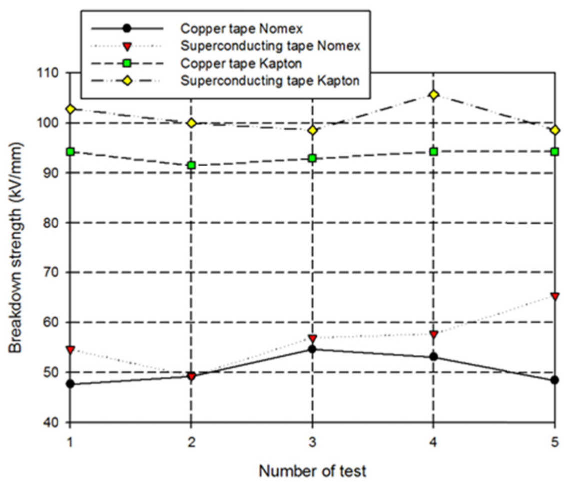

Figure 7. Relationship between the breakdown strength and the thickness of the Kapton sheet

3.2 Influence of the Thickness of the Tape on the Breakdown Strength

To study the influence of the thickness of the tape on the breakdown strength, the use of copper and superconducting tapes is compared. The superconducting tapes used in the experiments are provided by American Superconductor with a thickness of 0.3 mm, and the thickness of the copper tape is 0.1 mm. The parallel lapping method is adopted. Figure 8 shows the breakdown voltages of the Nomex and Kapton insulation layers. The breakdown strengths are calculated, and Table 1 lists the breakdown strengths from the sheet test with parallel lapping. The breakdown strengths of Nomex and Kapton are 50.6 and 93.4 kV/mm, respectively, when copper tape is used as the ground electrode. In comparison with the breakdown strengths of the dielectric sheet in LN2, the breakdown strength decreases by 9.6% and 19.5% for Nomex and Kapton, respectively. The copper tape has very sharp edges; thus, the electric field around these edges is highly non-uniform. The initial electrons are more likely to be produced here, and the partial discharge could be very intense. The breakdown strengths of Nomex and Kapton are 56.8 and 101.1 kV/mm when the superconducting tape is used as the ground electrode. In comparison with the breakdown strength of the dielectric sheet in LN2, the breakdown strength of Nomex is almost the same, yet the breakdown strength of Kapton decreases by 12.8%. From the experimental results, we can conclude that a very low thickness will lead to a decrease in the breakdown strength. This influence is more obvious for Kapton. For Nomex, the influence is minimal when the thickness is greater than 0.3 mm.

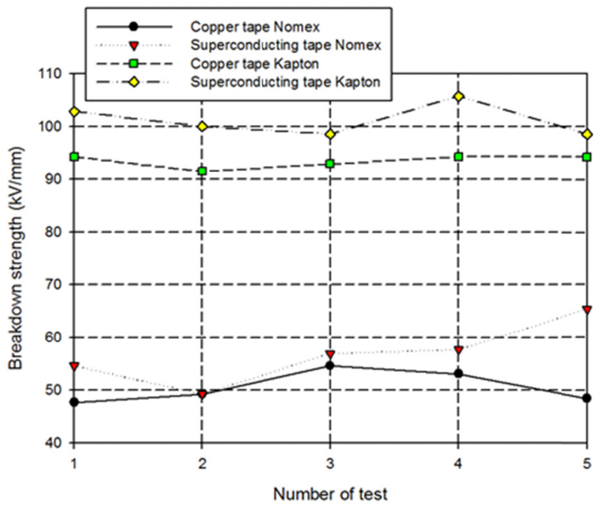

Figure 8. Breakdown strength when copper and superconducting tapes are used as the ground electrode for Nomex and Kapton

Table 1. Breakdown strengths of Nomex and Kapton using parallel lapping

Material	Sheet Test (kV/mm)	Copper Tape Used (kV/mm)	Superconducting Tape Used (kV/mm)
Nomex	56	50.6	56.8
Kapton	116	93.4	101.1

3.3 Comparison Between Parallel Lapping and Vertical Lapping

Figure 9 shows the breakdown voltages of the insulation layer when it is lapped onto a copper tape using the parallel and vertical methods. Both Nomex and Kapton are tested, and a copper tape is used as the ground electrode. For parallel lapping, the breakdown strengths are 50.6 and 93.4 kV/mm for Nomex and Kapton, respectively. For vertical lapping, the breakdown strengths are 60.6 and 104.9 kV/mm for Nomex and Kapton, respectively. Compared with the experimental data of parallel lapping method, the vertical lapping method can increase breakdown strength by 19.8% and 12.3% for Nomex and Kapton, respectively. Parts of the insulation layer are double-layered when vertical lapping is used. This is may be the reason why vertical lapping has a higher breakdown strength. However, this enhancement is very limited because vertical lapping is more likely to introduce air bubbles and other impurities. In addition, the breakdown voltages are more dispersed when the vertical lapping method is adopted. When the breakdown point is in a one-layer area, the breakdown voltage is relatively low; however, the breakdown voltage is relatively high when the breakdown point is in a double-layer area.

3.4 Face-to-Face Electrode Breakdown Test

To simulate the actual working conditions in a tape coil, face-to-face breakdown tests are conducted. The high-voltage and ground electrodes are made of superconducting tape lapped in the insulation layer with the parallel lapping method. The high-voltage and ground electrodes are pressed together face-to-face with a G10 slug and Teflon screws. Two layers of insulation material exist between the electrodes in this structure. The breakdown voltages are presented in Figure 10. It is shown that the breakdown voltages are only 1.3 and 1.2 times of the value of one layer of insulation for Nomex and Kapton, respectively. The breakdown strengths are only 38.1 and 62.9 kV/mm for Nomex and Kapton, respectively, in this insulation structure and decrease by 32.9% and 37.8%, respectively. The results show that the face-to-face insulation structure will lead to a very significant decrease in the breakdown strength and will affect Kapton more than Nomex.

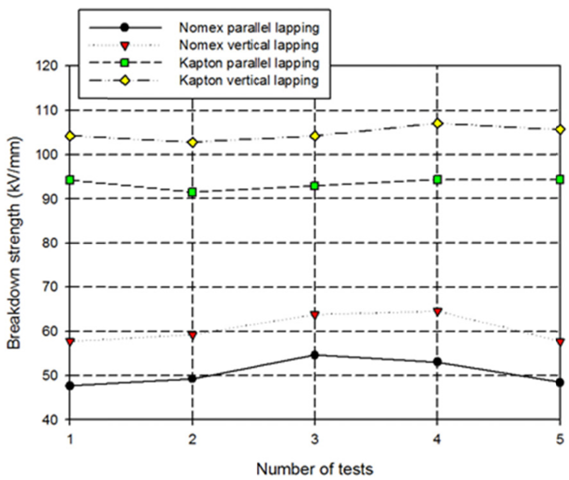

Figure 9. Breakdown strength of parallel and vertical lapping for Nomex and Kapton

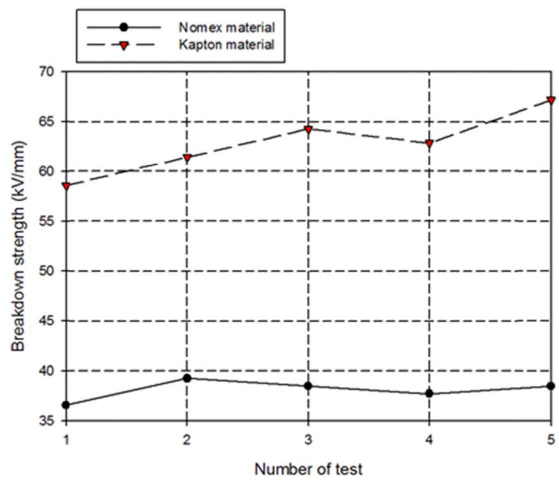

Figure 10. Breakdown strength of a face-to-face insulation structure for Nomex and Kapton

4. Conclusion

The basic insulation properties of Nomex and Kapton sheets are tested in air and LN2 using a newly fabricated test platform. The breakdown strengths of both insulation materials will greatly increase in LN2. The breakdown strength of Kapton is higher than that of Nomex, and the complex insulation effect is observed for Nomex.

On the basis of the conceptual design of a pancake-structure resistive-type SFCL, superconducting tapes should be lapped with an insulation layer. The breakdown strength of the insulation material will significantly decrease when lapped onto the tape. This is most likely because the tape is very thin and has very sharp edges at which partial discharge is more likely to occur. It is also shown that Kapton is far more sensitive to the thickness of the tape than Nomex. When the tape thickness is greater than 0.3 mm, the breakdown strength of Nomex remains the same. The influence of the thickness of the tape on the breakdown strength is verified. Two lapping methods are used in this study: parallel and vertical lapping. The comparison between these two methods shows that vertical lapping has better insulation performance, but the increase is very limited owing to the greater chance of introducing bubbles and impurities. Further, face-to-face breakdown tests are conducted to simulate the actual working conditions in a tape coil. The coil structure will greatly weaken the breakdown strength of the insulation layer. The results obtained can be used to design and optimize the geometrical structure of pancake resistive-type SFCL components.

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