Growth characteristics of electrical trees in epoxy resin at cryogenic temperatures

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Abstract. The electrical tree aging problem of epoxy resin has serious impacts on the insulation structure of superconducting magnet. It is necessary to investigate the growth characteristics of electrical trees in epoxy resin at cryogenic temperatures. The experimental system with a microscopic observation apparatus and a cryostat filled with the liquid nitrogen (LN2) was set up. Each group of samples was tested at a range of AC voltages from 8 kV rms to 20 kV rms and the partial discharge (PD) experiments were carried out at 298 K and 77 K. The results showed that the generation of electrical trees was resisted strongly at cryogenic temperatures. The growth of electrical trees was slower and the tree inception voltage increased obviously at cryogenic temperatures. Meanwhile, the degree of damage to materials caused by partial discharge at cryogenic temperatures was even more severe than that at room temperature.

1. Introduction
In the superconducting tokamak used in nuclear fusion, the insulation structure which is mainly composed of epoxy resin must withstand the harsh environment of cryogenic temperatures. When the fusion reactor is operated normally, the superconducting magnet is in a superconducting state, and the voltage it needs to withstand is almost zero. However, once the superconducting magnet is quenched, the whole device will have to withstand an extremely high voltage in an instant [1,2,3]. Therefore, in order to ensure the normal operation of the superconducting magnet and improve the safety and reliability of the device, the insulation material must have sufficient electrical insulation strength and an extremely high breakdown voltage. It is necessary to study the electrical insulation properties of epoxy resin under high voltage at cryogenic temperatures.
Electrical aging caused by electrical trees can lead to the breakdown of insulating materials. In the manufacturing process, bubbles and impurities will be introduced into the epoxy resin, which causes local electrical field concentration. Partial discharge and charge injection will lead to the formation of electrical branch channels [4]. Much research has been done on the growth properties and development mechanisms of electrical trees, and many improved methods to prevent electrical aging have been proposed [5,6]. However, it is worth noting that most of studies were carried out under room temperature. A few studies on the electrical tree characteristics of epoxy resin have been conducted under cryogenic temperatures [7,8]. Once insulating materials are in an environment of lower temperature, its internal molecular structure and lattice vibration maybe change, and the development of electrical trees will become different. In this paper, the effects of cryogenic temperatures on the growth of electrical trees are analysed under different AC voltages. Several characteristic parameters such as inception proportion, inception voltage, and growth rate are discussed to interpret the growth characteristics of electrical trees at cryogenic temperatures.

2. Experimental

2.1. Sample preparation
In this work, the epoxy resin material consists of bisphenol F epoxy resin and DETDA curing agent in a ratio of 100:24. As shown in Fig. 1(a), the diameter of the needle electrode was 0.18 mm. The radius of curvature of the tip and the cone angle were 2 μm and 30° respectively. The distance between the tip and the bottom of the sample was 3 mm. and the size of the epoxy resin sample was 130 mm × 20 mm × 4 mm (length × height × width), in which 13 steel needles were inserted at equal intervals of 10 mm. Before the test, the sample was tightly held between high-voltage electrode and ground electrode. The two electrodes were fixed by two non-conductive PTFE screws, as shown in Fig. 1(b).

![Figure 1](image_url)

**Figure 1.** (a) Epoxy resin sample; (b) Sample fixture.

2.2. Experimental system and test method
As shown in Fig. 2(a), the experimental setup at room temperature mainly consists of a high voltage AC power system and a digital microscope imaging system. The test sample was placed in a round quartz vessel filled with silicone oil to avoid electrical flashover along the surface of the sample. In addition, silicone oil can also improve the clarity of the viewing
system. The digital microscope imaging system includes a Nikon optical microscope (SMZ1000) and a PC. The microscope is connected to a PC via a CCD camera for real-time image capture of electrical trees. The initiation, development, and structures of the electrical trees are recorded. As shown in Fig. 2(b), compared with the experimental setup at room temperature, the experimental setup at cryogenic temperatures has a temperature acquisition system and a LN2 transmission system. The temperature acquisition system records the real-time temperature of sample until the temperature is stable at 77 K. The room temperature is recorded as 298 K and the applied voltages are 8, 12, 16 and 20 kV rms respectively.

![Figure 2](image)

**Figure 2.** Partial discharge experimental device at (a) 298 K and (b) 77 K.

3. Results and discussion

3.1. Tree Inception Proportion and Structures

![Figure 3](image)

**Figure 3.** Tree inception proportion.

Tree inception proportion changes with the temperature, which is defined as the ratio of the number of samples which generated electrical trees to the total number of samples after 15 minutes of voltage application, and the standard length of tree inception is 10 µm. The result is shown in Fig. 3, where it can be found that the generation of electrical trees is resisted strongly and the tree inception voltage increases obviously at 77 K.

The voltage amplitude and temperature have a great influence on the partial discharge inside epoxy resin, which results in different structures of electrical trees. The typical structures of electrical trees with different voltage amplitudes are shown in Fig. 4. At room temperature, the structure of electrical trees in the epoxy resin is a typical branch tree, with few branches on the trunk. At 77 K, the colour of electrical trees is deepened, and there are many thin branches on the trunk. These branches are interlaced, making the structures of
electrical trees more complicated. That means the damage caused by the aging of electrical trees at cryogenic temperatures is more serious than that at room temperature.

![Figure 4](image)

**Figure 4.** The structures of electrical trees.

3.2. Tree growth properties

![Figure 5](image)

**Figure 5.** The growth rate of electrical trees at 298 K and 77 K.

Fig. 5 shows the effect of cryogenic temperatures on the growth rate of electrical trees. It can be found that the growth rate of the electrical trees decreases significantly at 77 K, indicating that cryogenic temperatures can inhibit the growth of electrical trees.

When the voltage amplitude is lower than 12 kV, the growth rate of the electrical trees is very slow, and the temperature is the main influence, which is related to the amount of charge injected and derived at the needle tip per unit time [9]. Once the voltage amplitude exceeds 12 kV, the growth rate of the electrical trees at room temperature will increase greatly, and the electrical trees will rapidly develop to the ground electrode within 2 hours. After that, the growth rate of electrical trees decreased to a very low level. However, the growth of electrical trees at 77 K shows an opposite trend. In the first 600 minutes, the growth rate of electrical trees is slow. Then the growth of electrical trees accelerates obviously, which can be attributed to the effect of cryogenic temperatures on the accumulation of carbides in the branch channels [10]. The energy accumulated inside the epoxy resin is quickly taken away
by LN$_2$, and more and more carbides accumulate in the branch channels, which leads to the enhancement of conductivity of the tip of branches.

Conclusion

The voltage amplitude and temperature have a great influence on growth characteristics of electrical trees in epoxy resin. At cryogenic temperatures, the generation of electrical trees is resisted strongly, the growth of electrical trees is slower and the tree inception voltage increases obviously. Meanwhile, the degree of damage caused by discharge in epoxy resin at cryogenic temperatures is even more severe than that at room temperature.

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