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Influence of void defects on partial discharge behavior of superconducting busbar insulation

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HIGHLIGHTS

- PD detection method was used to check the quality of the superconducting busbar insulation.
- The samples with different void fraction were manufactured for comparing.
- The discharge inception voltage, PRPD pattern was tested and studied for the samples with different void content.
- The PD behaviors in oil bath and air condition were compared.

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ABSTRACT

For a magnetic confinement fusion device, the superconducting magnets and busbars need to be insulated with one layer of solid insulation to isolate the high voltage potential from the ground. The insulation layer commonly consists of several interleaved layers of epoxy resin-impregnated glass fiber tapes and polyimide films. The traditional electrical inspection methods for such solidified insulation on the magnet and busbar are a DC voltage test or a Paschen test. These tests measure the quality of the insulation based on the value of leakage currents. However, even if there is a larger quantity of high dielectric strength material implemented, if there are some microcavities or delaminations in the insulation system, the leakage current may be limited to microampere levels under testing levels over dozens of kilovolts. Therefore, it is difficult to judge the insulation quality just by the magnitudes of leakage current. Under long-term operation, such imperceptible defects will worsen and finally completely break down the insulation because of partial discharge (PD) incidents. Therefore, a PD detection test is an important complement to the DC voltage and Paschen tests for magnet and busbar insulations in the field of fusion.

It is known that the PD detection test is a mature technique in the electric power industry. In this paper, the PD characteristics of samples containing glass fiber-reinforced composite insulations for use with the superconducting busbar were presented and discussed. Various samples with different void contents were prepared and the PD behaviors were tested.

1. Introduction

Glass fiber-reinforced epoxy resin composites have been widely employed in the field of fusion engineering as electrical insulation on superconducting magnets and busbars [1]. The common curing techniques for such composites are the vacuum pressure impregnation, “wet-winding,” or the “pre-preg” technique [2]. Regardless of the insulation manufacturing technology adopted, it is almost impossible to eliminate defects in the insulation layers. The most common defect modes in these composite include voids, foreign inclusions, delaminations, and lack of fill out [3]. Among these types of defects, voids are an intrinsic defect mode, which can be generated easily during the tape wrapping and curing phases. A trapped void or air pocket will lead to partial discharge (PD) and localized electrical breakdown at first, and will eventually spread through the entire insulation thickness after long-term operation [4]. High operating or fault scenario voltages in the magnet and busbar may accelerate this condition.

The preliminary insulation inspection method for superconducting magnets and busbars are the DC voltage test at atmospheric conditions and the Paschen test, which installs whole high voltage (HV) components into a vacuum vessel to simulate the most crit-

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ical low gas pressure environment [5,6]. Owing to the polyimide film and the increasing insulation electrical safety margin, even with cracks in the insulation, the defects will not penetrate the layer, and the leakage current at the testing voltage is limited at the microampere magnitude level, whose value is similar to the insulation without defects. Therefore, the insulation quality judgment based on the leakage current needs to be modified to be more sensitive to the micro defects in the insulation.

PD detection developed over several decades in power devices and the electric industry. PDs are small electrical sparks that occur in the voids of the insulation and are a direct reflection of the inner condition of the insulation layer. Mature commercial PD detection and analysis systems can monitor and record PD events in many online and offline applications. Recognition diagnosis and interpretation of the PD signals are widely researched [7–9]. PD detection can be implemented in fusion magnet insulation inspections as an effective supplemental method for DC and Paschen tests.

To obtain an understanding of the PD behaviors in the glass fiber-/polyimide-reinforced epoxy resin composites for the superconducting busbar, different insulation samples with different void contents were manufactured. The samples were tested using the conventional PD test method in which the relationships of the leakage current, PD inception voltage, discharge phase-resolved discharge distribution, and pulse magnitude with the void content were discussed in this paper.

2. Experiment method

2.1. Insulation structure and curing technique

A plate type [10] insulation sample was prepared for the PD experiment. The insulation structure contained one layer of the glass fiber tape, nine layers of the glass fiber/polyimide (GK) compounding tape, and finally two layers of the glass fiber tape. Each layer was half-overlapped and wrapped on a plate type stainless steel mandrel, as shown in Fig. 1. To acquire samples with different void contents, the following insulation curing methods were used:

- Dry glass fiber- and polyimide-reinforced epoxy resin composite manufactured with wet-winding technique, curing under atmospheric air pressure.
- Pre-preg and polyimide tape composite manufactured with a vacuum bag.

Method I involves wet-winding technology. Resin impregnation is manual and curing occurs without vacuum. This method generates a higher void content than the pre-preg method. In method II, the insulation layer is made using pre-pregs and cured in a vacuum bag, while void content can be roughly adjusted by the curing pressure.

Materials used in the study are commercially available, including the glass fiber tape (0.21 mm thick and 25 mm wide, Sinoma, RW210A), polyimide film (0.05 mm thick and 21 mm wide, Dupont, Kapton-HN), the pre-preg tape (0.21 mm thick and 25 mm wide, Gurit SE84LV-RW210A, Gurit SE84LV-RW210A-Airstream), and the epoxy resin for the wet-winding process(Huntsman, Araldite GY282).

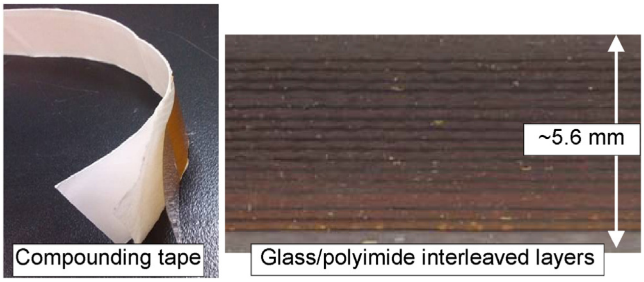

Fig. 1. Left picture shows the compounding GK tape; right picture shows cross section of insulation plate.

2.2. Void content measurement

Using the above raw materials and curing schemes, four different batches of insulation samples were prepared. The thickness of the samples was 5.6 ± 0.3 mm. The void contents were measured respectively for each sample with the ignition method. The test procedure was based on the standards in ASTM D2734 [11], and the void content was finally calculated from the measured density and theoretical density. The void contents of the four samples are summarized in Table 1, in which the sample prepared using the wet-winding method has the highest void content (over 7%), while the sample made using the Gurit pre-preg with SE84LV-RW210A-Airstream curing in a vacuum bag, has the lowest void value, which is close to zero.

The void diversity of the samples is reflected directly from the cross section optical microphotographs with 50 times magnification, as shown in Fig. 2. The microcavities distribute in the insulation layers with a scale from approximately 0.05 mm to 0.5 mm.

2.3. Experimental setup

The schematic of the experimental setup and the electrode arrangement are shown in Fig. 3. The electrical circuit was for the conventional PD measurement: the current pulse method. The test equipment was an OMICRON MPD600 system [12], which was connected in parallel to the sample. The PD and voltage signal were detected through a 1000 pF coupling capacitor, then sent through the measurement impendence unit, acquisition unit, and finally transferred to a personal computer for monitoring and recording.

The electrodes were a pair of rod-plane electrodes with a diameter of 25 mm and fillet radius of 3 mm. The electrodes were installed in a ceramic tank, which could contain transformer oil for eliminating the surface discharge effect to the test results in the air. The plate sample was cut to a rectangle measuring 100 mm × 70 mm and fixed between the electrodes immersed in the oil. Test specifications followed the standard IEC60270, and the bandwidth ranged from 100 kHz to 400 kHz, while the highest PD pulse was recorded in an interval of 20 μs. Before the test, the charge calibrator was connected to the circuit. The temporary grounding was removed for charge calibration. After calibration, the calibrator was disconnected.

The leakage currents, PD inception voltage, and phase- resolved PD pulse distribution of each sample were measured. The samples were tested and compared with and without transformer oil.

3. Experimental results and discussion

3.1. Leakage current

The relationship between the leakage current and applied voltage was observed during the experiment. Fig. 4 shows the test results. The AC test voltage was applied from 0 to 10 kV and converted to an electrical field, which is approximately 3 kV/mm. The leakage currents of different sample do not show a clear relationship with the void content of the samples. The value of the leakage current was limited at several tens of microamperes. The main reason was the large amount of Kapton film (Nine overlapping layers with a total thickness of 0.9 mm) used in the insulation structure.

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