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Statistical analysis of moisture's effect on AC breakdown strength of TiO_2 nanofluids

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ABSTRACT

Transformer oil-based nanofluids are widely investigated and exhibit an outstanding dielectric breakdown strength. Traditionally, the modifying effect of nanoparticles on the insulating properties of transformer oil is evaluated by average breakdown voltages. Little attention, however, was paid to the data dispersion of breakdown voltage of nanofluids. In this work, three types of statistical analysis methods including Normal, Gumbel and Weibull distributions were employed to analyze the AC breakdown performance of both mineral oil based TiO_2 nanofluids and pure mineral oils with different levels of moisture contents. And the applicability of all the three distribution methods for estimating the low probability breakdowns of the nanofluids was discussed. The three parameters Weibull was found to give a best overall distribution fit. The weakest link theory was used to explain the effects of TiO_2 nanoparticles on AC breakdown strength of mineral oil. TiO_2 nanoparticles can absorb dissolved water in oil, relieving the distortion of electric field and preventing the formation of conductive bridge in oil. Therefore, the resistance to moisture degradation of TiO_2 nanofluids was increased.

1. Introduction

Recently, transformer oil-based nanofluids with superior and unique physicochemical properties have provided a new way to improve the dielectric strength of transformer oil. It was found that the AC breakdown strength of transformer oil, by adding magnetic Fe_3O_4 nanoparticles, improved to 1.1 to 1.4 times depending on moisture contents [1,2]. To avoid the aggregation of magnetic nanoparticles under magnetic field [3,4], semi-conductive and insulating nanoparticles have been employed to modify the insulation of transformer oil [5,6]. Both ZnO [7,8], ZrO [7], Al_2O_3 [7], SiO_2 [8–10], GO [9] and TiO_2 [11,12] nanoparticles were found to increase the breakdown voltage of mineral oil, ester or propylene carbonate. Our research group prepared a type of semiconductive TiO_2 nanoparticles with oleic-acid surface modification [13–15]. By suspending the TiO_2 nanoparticles, both the AC and impulse breakdown voltage of new transformer oil and thermal aged oil enhanced significantly. Moreover, the breakdown strength of the TiO_2 nanofluid tended to strengthen increasingly under higher relative humidity level [16]. The higher breakdown strength makes nanofluids a potential alternative to conventional mineral oil for the application in electrical insulation.

The breakdown strength of insulating oils was generally judged by the average value of five to seven breakdown voltages in engineering situation [17,18]. However, the dielectric breakdown of dielectric liquids under AC electric field is a random phenomenon. The data dispersion of breakdown voltage value depends upon not only the physicochemical properties of liquids but also the electrode arrangement and impurities [19–23]. Water, introduced inevitably during production, transportation and operation processes, is one of the most common types of impurities in transformer. In bulk oil gaps, the dissolved water would distort the electrical field and form a bridge across the oil gap to initiate breakdown [24]. With moisture contents increasing, the breakdown voltages of oil would become more scattered. In order to help developing a better understanding of the AC breakdown performance of nanofluids, it is necessary to analyze enormous data of nanofluids' breakdown voltage.

In this paper, we prepared a stable transformer oil based TiO_2 nanofluid. Sixty breakdown voltage measurements of both pure transformer oil and nanofluid samples with different moisture contents were performed. Then the Normal, Gumbel and Weibull statistical tools were used to evaluate the discrepancies in breakdown voltage distributions between the pure oil and nanofluid samples. The breakdown voltage with low probability of both samples was calculated to test the adaptability of statistical tools. And the effects of TiO_2 nanoparticles on AC breakdown characteristics of transformer oil were analyzed. Eventually, the possible mechanism responsible for the increased AC

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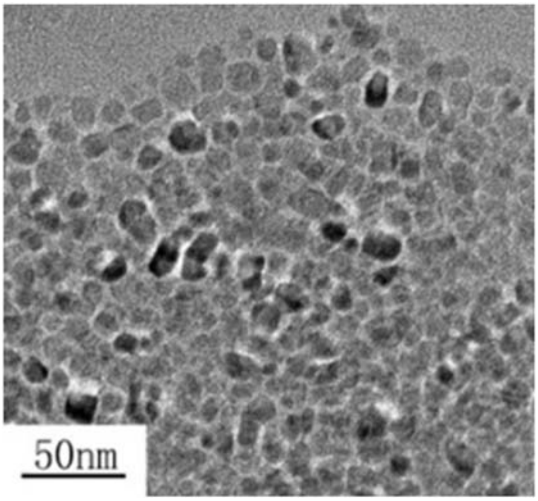

Fig. 1. HRTEM image of TiO_2 nanoparticles.

breakdown strength of TiO_2 nanofluid with high moisture level was discussed.

2. Experimental descriptions

2.1. Sample preparation

TiO_2 nanoparticles were prepared by a solvothermal method. Initially, titanium *n*-butoxide and DI water as reactants were introduced into a mixed solution of cyclohexane and triethylamine under continuous stirring. Additionally, oleic acid was added into the above solution at room temperature with vigorous agitation after stirring for 5 min. The resulting mixture was subsequently heated at the temperature of 150 °C for 24 h. The resulting product was then cooled down naturally and washed with distilled water and absolute ethanol for several times to remove the remained ions. High Resolution Transmission Electron Microscopy (HRTEM) image of the prepared TiO_2 nanoparticles is shown in Fig. 1. It is evident that the particles are in spherical shape and their average diameter is approximately 20 nm.

The prepared TiO_2 nanoparticles with volume fraction of 0.075% were suspended into the mineral oil (25# Karamay) through a ultrasonic bath for 10 min. The selected mineral oil was pre-filtered through a PTEE membrane filter by three times to remove the impurity particles. The membrane filter was provided by Pall Corporation and the porous diameter was 0.2 mm. The filtered oil could fulfill the requirement of clean oil defined by CIGRE working group 12.17, which clarified that

Fig. 2. Transformer oil (left) and TiO_2 nanofluid (right).

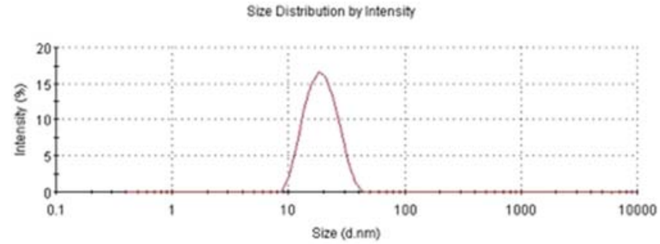

Fig. 3. Size distribution of nanoparticles in TiO_2 nanofluid.

the particle content with a diameter larger than 5 μm should be limited to 300 per 100 ml. The oil samples were then dried at a vacuum oven with a pressure of <100 Pa at 85 °C for 48 h. As shown in Fig. 2, there is no big difference in appearance between the prepared TiO_2 nanofluids and pure oil. The TiO_2 nanofluid is transparent with no sediment in the bottom. The size distribution of suspended TiO_2 nanoparticles in the nanofluid sample was measured by a Malvern ZS90 laser particle size analyzer. As shown in Fig. 3, the average diameter of nanoparticles is 20 nm after the whole treatment procedure indicating a high colloidal stability of the prepared nanofluid sample.

In order to study the effect of moisture on the AC breakdown characteristic of the TiO_2 nanofluid, oil samples with different moisture contents were prepared by using an environment chamber with controllable temperature and moisture level. By controlling the moisture level of atmosphere in the chamber, four groups of oil samples were obtained. The moisture contents of oil samples were measured by using a Metrohm 831 KF Coulometer according to Karl Fischer titration method before testing, which are listed in Table 1.

2.2. Experimental details

The AC breakdown voltage of oil was measured by using A Portable Jiantong Oil Tester 6801 as per IEC 60156. The setup and test cell are shown in Fig. 4. The electrode arrangement consists of two identical spherically capped brass electrodes with a diameter of 36 mm. The electrode gap distance is 2 mm and the voltage ramping rate is 2 kV/s. The initial standing time before test is set to 5 min. There is also 1 minute stirring time between each measurement. All experiments were carried out at room temperature. Sixty breakdown voltage measurements were taken for each sample.

To use the statistical tools, the most likely probabilities of breakdown were approximated by [25]

$$F(i,n) \approx \frac{i-0.44}{n+0.25} \tag{1}$$

where i represents the rank of data in order from smallest to largest in n breakdown times. Parametric distribution tools, including Normal, Gumbel, and Weibull models were used to analyze the obtained breakdown voltage. And non-parametric statistical analysis was used to test the accuracy of the parametric distribution models.

Table 1
The moisture content in oil samples.

(ppm)	Pure oil	Nanofluid
Group A	13.28	12.84
Group B	22.20	20.50
Group C	30.21	30.04
Group D	41.86	44.36