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Effect of Cellulose Particles on Breakdown Voltage in Wet FR3 Natural Ester

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ABSTRACT Due to the polar nature of natural ester, moisture content which may cause deterioration of electric strength is significantly higher in natural ester than that in mineral insulating oil. While the polarity of cellulose particles is stronger in terms of molecular structure than that of the natural ester, the breakdown voltage would be changed with increasing moisture and the cellulose particles. In light of this, the paper presents experimental studies on the effect of cellulose particle on breakdown voltage in wet FR3 natural ester. The DC breakdown tests are conducted and the breakdown voltages for three particle contamination levels, normal, marginal and high are investigated with five moisture content intervals, i.e., less than 100 mg/L, 100-200 mg/L, 200-300 mg/L, 300-400 mg/L and 400-500 mg/L respectively. The results show that the increase of cellulose particle contamination significantly accelerates the formation of cellulose bridge. Both the cellulose particles and moisture content have notable effects on the DC breakdown voltages. Higher cellulose contamination level in FR3 can lead to the decrease of DC breakdown voltage and more remarkable effect can be observed under the combined effect of the moisture. Analyses based on the relative dielectric constant and DC resistivity of the natural ester indicate that the reduction of the natural ester dielectric strength may be mainly attributed to the sharp decrease of the DC resistivity induced by the cellulose particles and the moisture. Also, the comparison of breakdown results between the DC and AC suggests the combined effect of particle and moisture in the natural ester breakdown behaviors.

INDEX TERMS DC voltage, cellulose particle, moisture content, breakdown characteristic, resistivity.

I. INTRODUCTION

As an insulating medium, mineral oil is widely used in power transformers and various high-voltage electrical equipment. However, mineral oil usually has a low ignition point and may cause great environmental pollution, which does not conform to the new concept of green power grid, so natural ester insulating oil refined from vegetable oils has become a research focus due to its advantages of high flash point, excellent biodegradability, good electrical performance and renewable ability [1]. The physical and electrical properties of natural esters have been investigated by many scholars. With the advance of technology, the natural ester insulating oil has basically been equivalent in the conventional test indexes, compared to traditional mineral insulating oil [2], [3]. Presently, the natural ester insulating oil has been applied in the distribution transformer and it is expected to be one of the most appropriate substitutes for the traditional mineral oil in the future.

Some impurities are inevitably mixed in the insulating oil of the transformer, including metallic particles mixed during the process of production and transportation, cellulose particles impurities brought by the oil-paper insulating structure and long-term operations, etc., and approximately 90 % of the impurities in transformer oil are cellulose particles [4]. The presence of particulate impurities can affect the insulating properties and increase risks of insulation breakdown which is known as the ‘particles theory’ [5], [6]. A number of researches about cellulose particles motion in mineral oil are published [7]–[10], describing different influence factors on cellulose particles bridging phenomenon in mineral oil. Different levels of particle contamination ranging from 0.001 to 0.024% by weight, different electric fields, i.e. DC, AC, and DC biased AC, and different electrode configurations, involving sphere-sphere electrodes and needle-plane electrodes are used to observe the dynamics of particle in contaminated transformer oil. Experimental results

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show that different voltage types can affect the motion characteristics of impurity particles in the transformer oil, thereby affecting the oil gap discharge and breakdown characteristics.

Additionally, many studies on breakdown strength has been performed under both AC and impulse voltages. Dr. W.R. Bell [11] launched a research on the AC breakdown strength of technical grade transformer oil, and three kinds of electrodes (i.e. Bruce profile brass electrodes, small mild steel electrodes and large mild steel cylindrical electrodes) were used to carry out this experimental work to observe changes in the average strength with successive discharges. Wang and Wang [12] investigated the AC withstand voltages of 'as-received', 'processed' mineral and ester transformer oil, respectively chose mineral oil, synthetic ester and natural ester, and combined the influence factors of moisture content to test the breakdown characteristics. It turns out that the average breakdown voltage, the highest breakdown voltage and the lowest breakdown voltage of the 'processed' oil are all higher than that of the oil containing impurities. Meanwhile, water can decrease the breakdown voltage to a certain extent for both oil samples. Zhao [13] undertook the impulse voltage test of three cellulose particles concentration (low, marginal and high) under four kinds of impulse voltage waveforms (1.4/50μs, 14/220μs, 80/850μs, 240/2400μs) in the mineral oil. The results suggest that the impulse voltage waveform parameters have a significant effect on the breakdown voltage and breakdown time, and an increment in the concentration of cellulose particles result in a reduction in the breakdown voltage. Furthermore, research in [14], taking standard lightning impulse voltage into consideration, explored the effect of cellulose particles on breakdown mechanism of synthetic ester and natural ester in uniform electric fields. The results indicated that the lightning impulse voltage reduces gradually with the increase of particle contaminations or moisture content and an increase of particle content can also lead to the decrease of breakdown time.

From the above studies, it can be speculated that when cellulose particles are in combination with moisture, the dielectric performance of the insulation oil may be significantly undermined, which may be more serious in natural ester, for one striking difference between natural ester and mineral oil lies in saturated water content. For example, at room temperature, the saturated water content of mineral oil (KI 25X) is about 56 mg/kg, while that of natural ester (FR3) is up to 1000 mg/kg, so the specified value of the moisture content in natural ester is set much higher than that in mineral oil. According to [15], it is stipulated that the limit of moisture content in natural ester insulating oil before the operation of 35 kV distribution transformer is 300 mg/kg. Because of the strong water imbibition of cellulose particles, the higher moisture content in natural ester may cause the cellulose to absorb more water and affect the movement and aggregation characteristics of cellulose particles, which may give rise to a variation of insulating properties of natural ester.

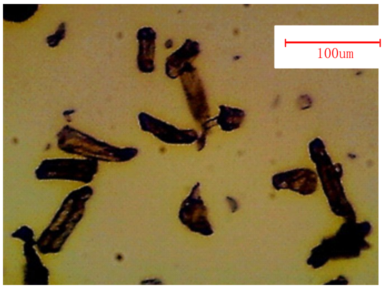


FIGURE 1. Optical microscopic image of cellulose particles.

In order to gain a better understanding of the insulation properties of natural ester with the presence of celluloses particles and moisture, this paper is devoted to the effect of cellulose particle on DC breakdown voltage and AC breakdown voltage in wet natural ester. The motion characteristics of cellulose particles in the oil gap are observed and the effect of particle contamination and moisture content on the DC and AC breakdown mechanism are also explored.

II. EXPERIMENTAL DESCRIPTIONS

A. SAMPLE PREPARATION

The natural ester FR3 produced by Cargill is selected in this experiment. For the exclusion of moisture and other impurities interfering with the test, the oil sample should be pretreated first. The pretreated process includes oil filtering by an organic filtration membrane with a pore diameter of 0.2 μm and drying treatment.

According to Cigre Technical Brochure 157, the insulating oil is classified into five contamination levels, i.e., nil, low, normal, marginal and high. During the experiment in this paper, it is found that the filtered insulating oil can reach the low level. However, the particle content of the oil sample will increase again after contact with air in the experimental process. In addition, since the breakdown test also results in the increase of particle content, it is difficult to maintain nil and low level during the experiments. Therefore, the normal-level, marginal-level and high-level oil samples are configured respectively in this paper. Firstly, dry cellulose particles are added to the oil samples quantitatively and the mass of cellulose particles in each oil samples was 0.004 g, 0.016 g and 0.006 g per 1000 mL, so that the cellulose particles concentration in the FR3 natural ester oil can reach the level of normal, marginal and high level respectively. Then the oil samples with three contamination levels are configured. The optical microscopic image of cellulose particles is shown in Figure 1. The particles are elongated or ellipsoidal-shaped in length ranging from several micron to 150 μm. Then, a magnetic stirrer is added to the oil samples to distribute the particles evenly. Finally, the oil sample mixed with the cellulose particles is placed in a vacuum drying oven, where the air pressure is less than 133 Pa and the temperature is 80 °C. The condition lasts for 48 hours until the cellulose particles are impregnated adequately, and it helps to remove the dissolved gas and moisture in the oil as well.

FIGURE 2. Hemisphere-hemisphere electrode system.

B. TEST SETUP

The hemisphere-hemisphere electrodes used in the experiment are made of copper with a 25 mm curvature radius, the distance between electrodes is 2.5 mm, and the edge of the electrodes is chamfered and polished to prevent electric field distortion, as is shown in Figure 2.

One end of the electrode is connected to a positive polarity HVDC power, and the other end is grounded. The digital camera is used to observe and record the motion of cellulose particles.

C. THE PROCEDURE

The moisture content of oil sample is determined by average value of the moisture content at the start time and the end time in this experiment, considering that the moisture content of oil samples at the beginning of the test differs from that at the end on account of the influence of air humidity. Furthermore, the moisture content ranging from 0-500 mg/L is categorized into five intervals i.e., less than 100 mg/L, 100-200 mg/L, 200-300 mg/L, 300-400 mg/L and 400-500 mg/L. The oil samples are grouped in light of the moisture content and classified into corresponding moisture content intervals.

1) TESTS FOR THE DRY SAMPLE

Keep the moisture content of the oil samples fixed in the same interval range (lower than 100 mg/L for the dry samples) during the whole test, and the breakdown tests are conducted on the oil samples with three contamination levels involving the normal-level, marginal-level and high-level respectively.

There is no specific standard for DC breakdown testing in FR3 natural ester so far, therefore, referring to the IEC 60156, ASTM D1816 and ASTM D877 standards for AC breakdown test, the paper chooses the continuous increase method and the DC voltage rising speed is 1kV/s increasing from zero until breakdown occurs.

In order to ensure valid statistical analysis of experimental data, a series of 18 breakdown tests are carried out for each contamination level and the oil sample is replaced every 6 effective breakdowns. Oil samples are stirred by a magnetic stirrer to assist the diffusion of the particles after each breakdown, and then stand still for 2 minutes to restore the uniform distribution of cellulose in the oil. All tests are performed under room temperature (20 °C) and both the particle motion images and the breakdown time are recorded by the digital camera.

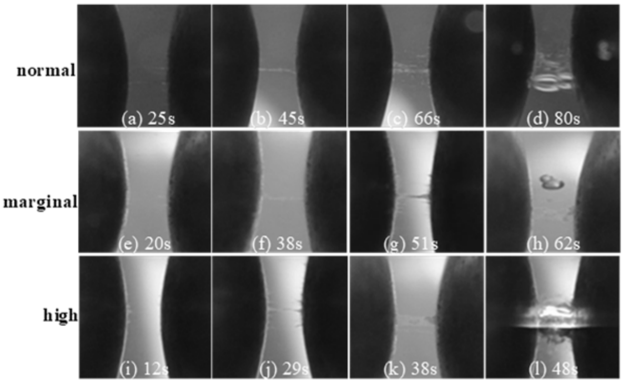


FIGURE 3. Cellulose particle motion dynamic diagram in three contamination levels of FR3 with moisture content of 50-100 mg/L.

TABLE 1. Breakdown times vary with particle contamination level and moisture content.

	Normal	Marginal	High
<100 mg/L	80s	62s	48s
100-200 mg/L	69s	54s	42s
200-300 mg/L	57s	47s	38s
300-400 mg/L	46s	39s	30s
400-500 mg/L	33s	23s	12s

2) TESTS CONSIDERING MOISTURE EFFECT

To explore the moisture content effect on the breakdown voltage of natural ester, oil samples with three contamination levels, normal, marginal, and high, are humidified in a chamber for 48 hours to fully absorb the moisture, while the chamber is set to a constant temperature with different humidity. The moisture content of the oil sample is measured by JWS-1 moisture detector, and then oil samples with different moisture are obtained. The methods and steps taken are the same as those in Test I used. Afterwards, the breakdown voltages of three different particle contents of insulating oil samples at different moisture contents are obtained. The average moisture content at the beginning and the end is taken as the measuring point in each breakdown test, and all tests are completed under room temperature (20 °C).

III. RESULTS AND ANALYSIS

A. EXPERIMENTAL OBSERVATION

Figure 3 shows the typical morphological changes of cellulose particles during the breakdown tests of the oil samples with moisture content less than 100 mg/L. and Table 1 demonstrates the breakdown time of oil samples varies with particle contamination levels and moisture contents.

Once DC voltage is applied, the motion of cellulose particles can be observed when it comes to 2-3 kV. At first,

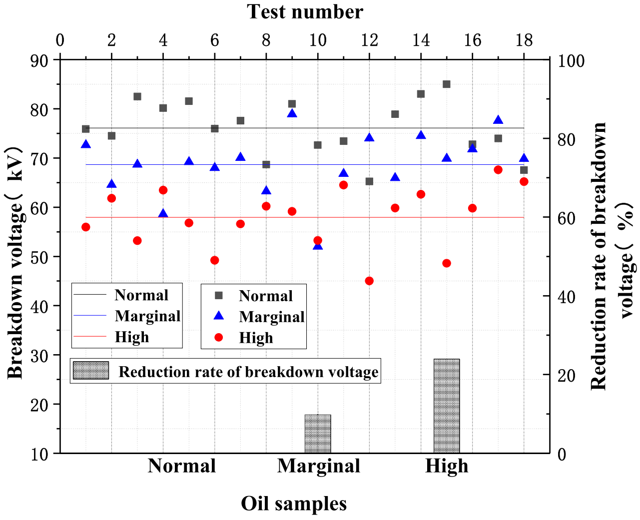


FIGURE 4. DC breakdown voltage of three kinds of oil samples with moisture content of less than 100 mg/L.

the cellulose particles suspended in the oil are drawn to electrodes surfaces due to dielectrophoretic (DEP) force. Some of the particles stay attached to electrodes surface and the others acquire charges from the electrodes and move back and forth rapidly between the electrodes under influence of DC electric field (Figure 3a, e, i). With the increase of voltage, the particles move faster and attract other oppositely charged particles until a skeleton of the bridge converges through the oil gap (Figure 3b, f, j). The bridge skeleton formed in the initial state is relatively weak with a small diameter and it may be prone to fracture as is observed in the experiment. Nonetheless, the cellulose bridge becomes stabilized gradually for higher voltage and longer duration time, with a larger diameter and a denser shape (Figure 3c, g, k). Finally, as the voltage continues to increase, the oil gap breakdown occurs along with the cellulose bridge, accompanied by the formation of bubbles (Figure 3d, h, l).

Comparing the processes of the bridge formation (45s, Figure 3b; 38s, Figure 3f; 29s, Figure 3j) and the breakdown time in Table 1, it can be concluded that the increase of cellulose particle and water content in oil samples can both accelerate the formation of cellulose bridge and lead to faster breakdown of oil gap.

B. THE BREAKDOWN VOLTAGE RESULTS

The DC breakdown result of three kinds of oil samples with moisture content of less than 100 mg/L is shown in Figure 4. The voltage drop percentage is calculated to investigate characteristics between voltage and contamination level. The scatter points present the breakdown data of three kinds of oil samples with different particle content. The three straight lines refers to the corresponding average breakdown voltage. Moreover, the breakdown voltages and distribution parameters of the three oil samples are given in Table 2. Comparing the distribution parameters of the three oil samples, the conclusion can be drawn that the cleaner oil gains higher breakdown voltages and less standard deviations. It is well known that breakdown is initiated by the 'weak link' in the oil, and less particles in the oil produce less 'weak links', therefore it is more difficult to initiate breakdown.

TABLE 2. DC breakdown voltages and distribution parameters of the three oil samples with moisture content of less than 100 mg/l.

	Normal	Marginal	High
Mean breakdown voltage (kV)	76.1	68.7	57.9
Highest breakdown voltage (kV)	85	78.9	65.2
Lowest breakdown voltage (kV)	58.9	48.0	38.0
Standard Deviation (kV)	7.8	9.7	9.3
Coefficient of variation (%)	10.25	14.12	16.06
Normalized breakdown voltage (%)	100	90.28	76.08

Adopting the breakdown voltage of the normal-level oil samples as the normalized benchmark, the percentage of voltage drop can be calculated, as the histogram shows in Figure 4. It is observed that the breakdown voltage of marginal-level oil sample decreases by approximate 10%, whereas the high-level oil sample breakdown voltage falls approximate 25%. Overall, it suggests that the cellulose particle has a significant effect on the breakdown voltage of insulating oil. The breakdown voltage decreases obviously as the particle contamination level increases.

Based on the weakest link theory, the 2-parameter Weibull distribution model is adopted to statistically analyze breakdown data and effectively calculate the insulating oil breakdown probability, given by (1) [14], and the least square linear regression is used to estimate the model parameters.

$$F(t) = 1 - \exp[-(x/\alpha)^{\beta}] \tag{1}$$

where,

x: breakdown voltage

α: scale parameter

β: shape parameter

Figure 5 demonstrates the breakdown voltage for three kind of oil samples and the corresponding Weibull distribution parameters are described in Table 3.

The results above reveal that the DC breakdown voltage fits the Weibull distribution well. As cellulose particle content increases, the breakdown voltage tends to move to the left, indicating that the breakdown voltage gradually declines with contamination level increasing.

C. PARTICLE EFFECT AT WET OIL CONDITION

In view of the test mentioned previously, the DC breakdown voltages of normal, marginal and high oil samples with the

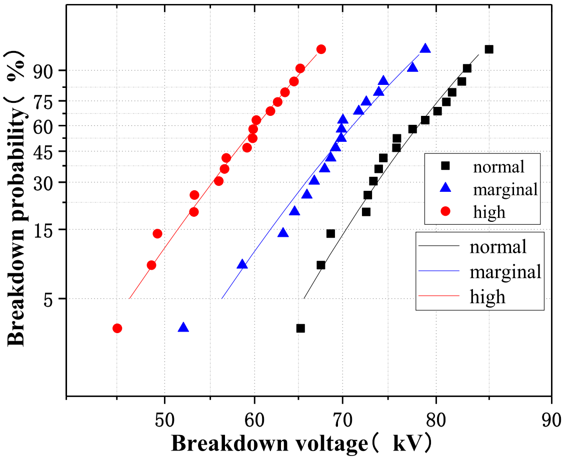


FIGURE 5. Weibull distribution of breakdown voltage for three kinds of oil samples.

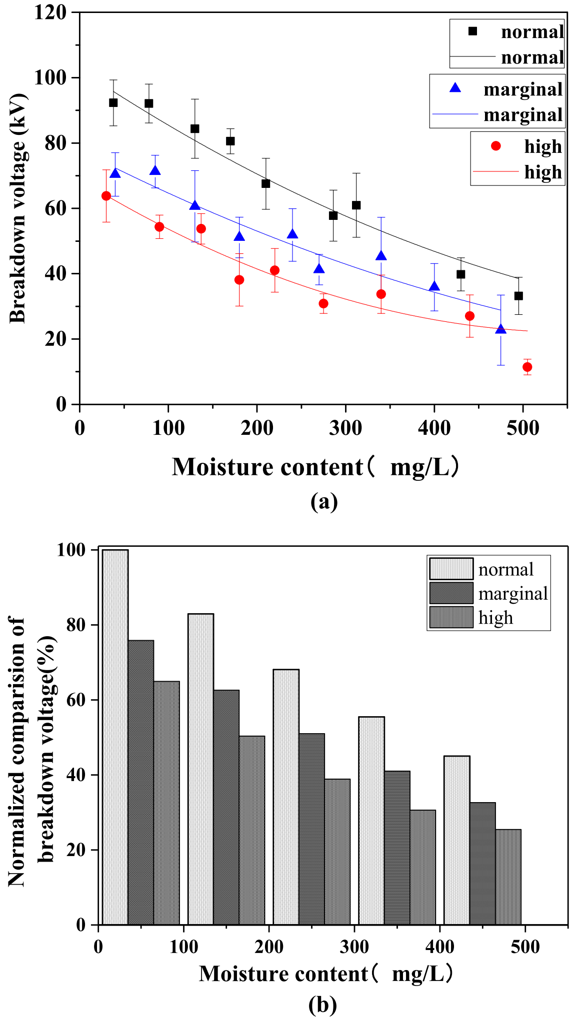
TABLE 3. Weibull distribution parameters.

Parameter	Normal	Marginal	High
α	78.62	71.60	60.68
β	16.42	12.34	10.98
Correlation coefficient	0.987	0.986	0.993

change of moisture content are obtained, as is shown in Figure 6(a). The curves are obtained by quadratic polynomial fitting of the scatter plots.

It is found by comparison that for the same contamination level, breakdown voltage decreases gradually with the increase of moisture content; whereas the breakdown voltage reduces with the increase of particle contamination level at the same moisture content.

Take the median values of each moisture interval (i.e. 50 mg/L, 150 mg/L, 250 mg/L, 350 mg/L and 450 mg/L) as water content characterization of the oil samples. The breakdown results are normalized based on the breakdown voltage of normal-level oil sample at the moisture content of 50 mg/L in order to study the decreasing trend. Normalized comparisons of breakdown voltage for the oil samples are shown in Figure 6(b). As can be seen in conjunction with Figures 6(a) and (b), for the same moisture content, the breakdown voltage of the oil sample reduces as the particle contamination level increases. When the oil sample is dry (50 mg/L), the content of the particles increasing from normal to high level results in the breakdown voltage decline by about 35%; When the moisture content in the oil sample is high (450 mg/L), the particle content rises from normal level to high, causing breakdown voltage drop by nearly 45%. Similarly, for oil samples with the same particle content, the breakdown voltage decreases with the increase of moisture content. For the normal-level oil sample, the moisture content increases from 50 mg/L to 450 mg/L, which brings a breakdown voltage reduction of about 55%; for the high-level oil sample, the moisture content rises from 50 mg/L to 450 mg/L, leading to a 60% drop in breakdown voltage.



(a)

(b)

FIGURE 6. Relationship between DC breakdown voltage and moisture content for different cellulose particle contaminations.

Concerning the combined effect of particle concentration and moisture content, the breakdown voltage of high-level oil sample with a moisture content of 450 mg/L decreases by about 75% compared with the normal-level sample with a moisture content of 50 mg/L. In consideration of the moisture content of the site operating transformer oil (lower than 300 mg/L), the reductions of breakdown voltage are 32%, 50%, and 61% for the oil of normal, marginal and high contamination levels respectively. Hence, just as described herein above, the risk of a dielectric failure should be given enough attentions for the combined effect of particle concentration and moisture content in natural ester.

As a comparison, AC breakdown tests of normal, marginal and high oil samples with the change of moisture content are conducted according to the standard IEC 60156 and the result is shown in Figure 7.

The data of yellow dotted line in Figure 7 is from the Cigre Technical Brochure 436 for pure natural ester. The test result

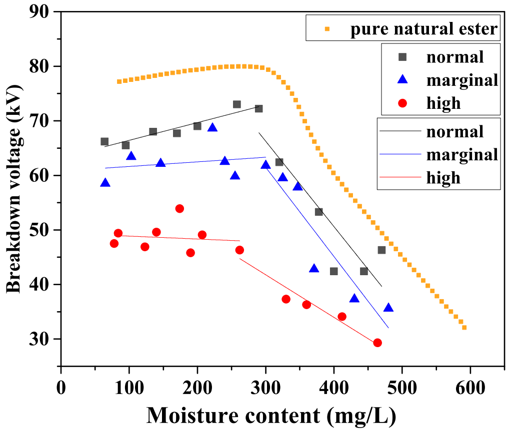


FIGURE 7. AC breakdown voltage of FR3 natural ester oil samples with the change of moisture content.

clearly illustrates that the AC breakdown voltage of natural ester oils changes from stability to fast decline when the moisture in oil samples increases over a critical value, which is exactly different from the change rule of DC breakdown test shown in Figure 6(a). Furthermore, with the increase of particle concentration, the moisture critical value indicated by the circle in the Figure 7 of these oil samples decreases gradually. Besides, comparing the trends of oil samples with three cellulose particle contents, it can be found that the AC breakdown voltages gradually reduce with the increase of particle concentration, which is consistent with the change rule of DC breakdown test.

IV. DISCUSSION

According to the test phenomena and breakdown voltage showed above, the mechanism of cellulose particles influence on DC breakdown voltage in wet FR3 natural ester can be explained as follows. The particle concentration and moisture content affect the breakdown characteristics of insulating oil by changing the basic parameters of insulating dielectric.

To verify the explanation above, researches on relative dielectric constant and volume resistivity of the oil samples are carried out based on standard IEC 60247. YCYJS9 dielectric loss and resistivity tester are used to test the dielectric parameters of the oil samples. The oil cup adopts a three-pole structure and the distance between electrodes is set at 2mm to eliminate the influence of stray capacitance and leakage on the test results. Test conditions are set to DC voltage 500 V, AC voltage 2000 V. In addition, considering the actual operating temperature of the transformer, 90°C is chosen as the test temperature.

Figure 8(a) demonstrates the relationship between moisture content and the relative dielectric constant of oil samples in three particle concentration levels. It is observed that the relative dielectric constant of the high-level oil sample is apparently larger than that of the normal-level oil sample with the same moisture content. Meanwhile, at the same particle contamination level, the relative dielectric constant grows moderately with the increase of moisture content.

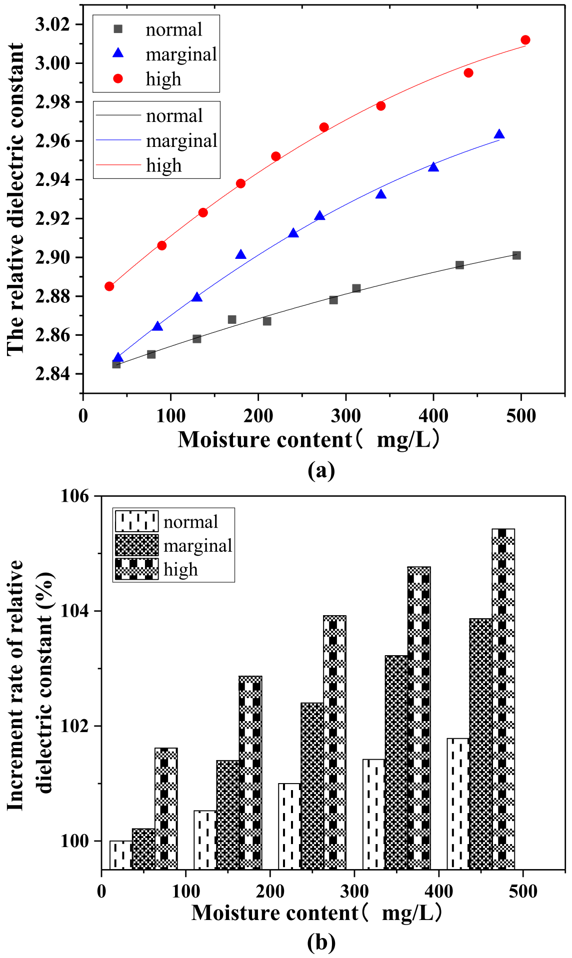


FIGURE 8. Relationship between relative dielectric constant and moisture content for different cellulose particle contaminations.

To compare the rangeability of the relative dielectric constant of three kinds of contamination oils with different moisture contents, a histogram is given in Figure 8(b). The calculation method is similar to that in Figure 6(b).

As is indicated in Figure 8 (a) and (b), the higher the particle contamination level, the larger the relative dielectric constant, when the moisture content is steady. When the oil sample is dry (50 mg/L), the content of the particles increases from the normal to high level, resulting in around 1.6% rise of the relative dielectric constant; when the moisture content in the oil sample is high (450 mg/L), the particle content rises from the normal to high level, causing the relative dielectric constant to drop by nearly 3.6%. Likewise, the higher the moisture content rises, the larger the relative dielectric constant will become, when the particle concentration is settled. For the normal-level oil sample, the moisture content increases from 50 mg/L to 450 mg/L, giving rise to a relative dielectric constant reduction of about 1.8%; for the high-level oil sample, the moisture content growing from 50 mg/L to 450 mg/L, leads to a 3.7% drop in relative dielectric constant.

As combined effect of particle and moisture on insulating oil is studied, it is found that the relative dielectric constant of high-level oil samples with a moisture content of 450 mg/L increases by about 5.4%, compared with that of the normal-level samples with a moisture content of 50 mg/L.

Based on the test results that the relative dielectric constant of insulating oil has a relatively tiny change influenced by cellulose particles and water, the mechanism is analyzed as follows: cellulose particles are polar solid dielectric and a vast number of polar groups exist in its molecule, such as hydroxyl polar groups, uronic acid groups, etc., which have a large intrinsic dipole moment. Hence, the dipole steering polarization dominates in the electric field. The addition of moisture facilitates the dipole steering polarization.

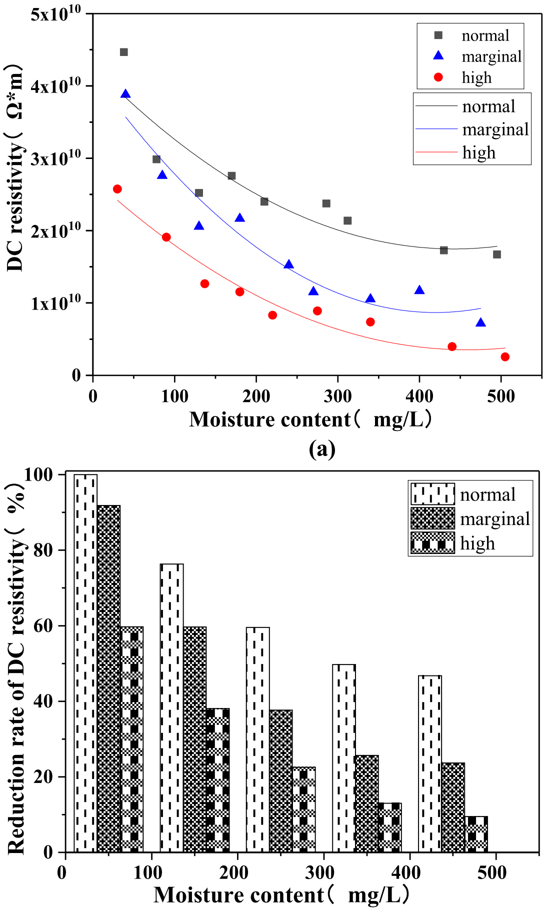
Under the action of electric field, the cellulose particles are subjected to DEP force, Coulomb force, van der Waals forces and repulsive force, and other forces [16]–[22]. However, J.A. Kok in [20] demonstrated that van der Waals force and repulsive force are both suitable for the particle diameter less than 500 Å, therefore, these two forces are negligible and the DEP force is one of the main forces attributed to the directional movement of cellulose particles. For cellulose particles in the insulating oil,

$$F_{DEP} = 2\pi\varepsilon_m r^3 \mathrm{Re}\left[K\left(\omega\right)\right]\nabla E^2 \tag{2}$$

where $\boldsymbol{E}$, r, ε_m, refer to electric field, particle diameter and relative dielectric constant, and $\mathrm{Re}[K(\omega)]$ is the real part of the Clausius-Mossotti factor.

DEP force is proportional to the relative dielectric ε_m constant known by (2). Therefore, the addition of particle concentration causes an increment of the DEP force which particles are subjected to, resulting in a violent movement between the two electrodes. Furthermore, it also accelerates the aggregation of cellulose particles at the ends of electrodes. However, as can be seen from Figure 8, the magnitude changes of ε_m is relatively small, which has a slight influence on the DEP force exerted on cellulose particles. Therefore, it cannot result in a significant decline in breakdown voltage of the insulating oil sample in Figure 6. Accordingly, it can be inferred that the change in the relative dielectric constant is not the main cause for breakdown voltage drop of the insulating oil.

For further research on the influence mechanism of cellulose particles and moisture on FR3 insulating oil, DC resistivity of three contamination level oil samples with 5 moisture contents is measured, and the results are shown in Figure 9(a), in which the curves are obtained by quadratic polynomial fitting of the scatter plots. It is clearly revealed that DC resistivity of the high-level oil sample is slightly below the marginal-level oil and apparently lower than the normal-level oil with the same moisture content; for the same contamination level, DC resistivity of the insulating oil reduces gradually with the increase of moisture content. In other words, increased moisture content and particle concentration lead to enhanced conductivity of the insulating oil.



(b)

FIGURE 9. **Relationship between DC resistivity and moisture content for different cellulose particle contaminations.**

Similar to the previous calculation method in Figure 6(b) and Figure 8(b), the DC resistivity of normal-level oil sample with 50 mg/L moisture content is regarded as the normalized benchmark, and results are demonstrated in Figure 9(b).

Figure 9 (a) and (b) suggest that the higher particle concentration is, the smaller DC resistivity will be, when the moisture content is settled. Besides, the higher the moisture content becomes, the smaller the DC resistivity will be, when the particle concentration is steady. When the oil sample is dry (50 mg/L), the content of the particles ascending from normal to high level causes DC resistivity a decline of about 40%; when the moisture content in the oil sample is high (450 mg/L), the particle content increases from normal to high level, which leads to a nearly 80% drop of the DC resistivity; when the content of the particles remains at a normal level, the moisture content of oil sample rising from 50mg/L to 450 mg/L results in DC resistivity decreasing by around 53%; when the particle content in the oil sample is at a high level, the moisture content climbing from 50 mg/L to 450 mg/L, brings about a 84% reduction in DC resistivity.

Studies on joint effect of particle and moisture content on DC resistivity of oil samples indicate that the joint effect leads to around 90% reduction of DC resistivity, which is a noticeable change, by comparison between high-level oil sample with 450 mg/L moisture content and normal-level oil sample with 50 mg/L moisture content.

In general, the relative dielectric constant and DC resistance of the oil sample are both affected by cellulose particles and moisture content under DC voltage. Specifically, the relative dielectric constant is under slightly influence, whereas the DC resistivity suffers acute impact exerted by the two. Combining the breakdown voltage in Figure 6, it is inferred that cellulose particles and moisture mainly affect the performance of insulating oil by changing resistivity.

The mechanism of DC resistivity effect on insulating oil property is analyzed as below. The increase of particle and moisture content leads to a reduction in resistivity of oil sample and the increase in corresponding conductivity of the oil sample. Consequently, the electrical conduction current between the electrodes increases. This suggests that in the insulating oil, originally uncharged cellulose particles turn to carrying charges under the action of electric field, and the charged particles in the oil gap move freely to form a conductive flow.

Under DC electric field, the charged cellulose particles are subjected to not only DEP force, but also Coulomb force, fluid drag and other forces [18]–[22], among which Coulomb force and fluid drag are the main forces, as given in (3) and (4).

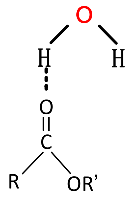
$$F_q = qE \tag{3}$$

$$F_{drag} = \frac{1}{2} C_d \pi r^2 \rho_1 (v_1 - v_2) |v_1 - v_2| \tag{4}$$

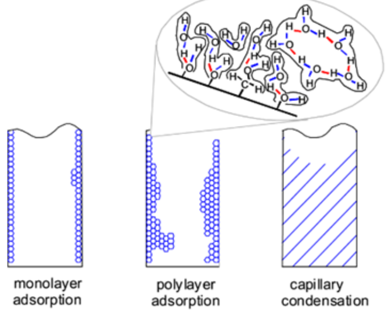
where C_d, ρ_1, v_1, v_2 refer to drag coefficient, oil density, oil viscosity and particle viscosity.

Under the action of DEP force, Coulomb force and fluid drag, positively charged particles move to the ground electrode, while the negatively charged particles move toward the high voltage electrode side and collide with electrodes. Once charged again on the electrodes, particles may be adsorbed on the electrode, or move to the opposite electrode due to Coulomb force. The described process can be seen clearly in Figure 3: particles first accumulate at surface of electrodes (Figure 3a, e, i); then, there is a formed bridge skeleton between the two electrodes (Figure 3b, f, g). The higher the content of cellulose particles in the insulating oil is, the denser the formed bridge is; the more moisture content become, the more sufficiently the cellulose particles are charged; the more intensely particles move, the less time the bridging process takes, which will result in lower insulating performance and more breakdown times of oil sample eventually. To put it another way, the DC breakdown voltage decreases as the conductivity increases.

The comparison of breakdown results between the DC and AC shows that the moisture plays different roles with AC and DC breakdown behaviors which is the combined effect of particle and moisture in the natural ester breakdown behaviors. These results may be determined by the physical and chemical properties of natural esters, cellulose particles and water.



(a) Ester attract water molecule (R and R' represent carbon chains, which may be the same or different)



(b)Adsorption of Water Vapour Molecules at Active Sites in Microcapillaries of Cellulosic Material [23]

FIGURE 10. The interaction of ester and cellulose with water molecules.

Water is a strong polar molecule and polar molecules tend to be most strongly attracted to other polar molecules. The structure of the natural ester is based on a glycerol backbone, to which 3 naturally occurring fatty acid groups are bonded. The natural ester linkages make the fluid 'polar', and these linkages are able to attract water molecules in a way mineral oil cannot. When the moisture content is low, the water dissolved in the natural ester evenly by forming hydrogen bonds with the polar part of the ester as is shown in Figure 10(a). The dielectric withstand strength will not be influenced much by the moisture and the natural ester can maintain AC breakdown voltage unchanged with increasing moisture levels.

While the polarity of cellulose particles is stronger in terms of molecular structure than that of the natural ester. Cellulose is a polymer structure made up of many glucose units arranged in chains. These polar units enable cellulose to actively attract and adsorb water molecules as is presented in Figure 10(b).

When there exist moisture and cellulose particles in the natural ester oil samples, cellulose particles and water molecules attract each other and bond together. The combined action can lead to increased polarity and decreased DC resistivity of natural ester oil samples. In the case of DC voltage, the direction of the DEP force and the Coulomb force stays the same, which will accelerate the directional movement and accumulation of cellulose particles in the oil gap, leading to faster formation of impurity bridge and more 'weak links' suspended in the oil. Therefore, the DC breakdown voltage decreases linearly with the increase of cellulose particles and moisture content. In the case of AC voltage, the direction of the electric field and Coulomb force changes periodically. When the content of cellulose particles and moisture is low, there are fewer particles suspended in the oil. As the natural ester oil is moistening by water, there is little chance for the water molecule to combine with particles to form conductive ‘weak link’ in the oil. Accordingly, the combined effect of water and cellulose particles is difficult to play a role due to the strong water solubility of natural ester, and the natural ester can still maintain a high breakdown voltage.

When the moisture in oil samples increases over a critical value, the conductive particles which is formed by cellulose particles absorbing water cause deterioration of electric strength. The polarity of cellulose particles is stronger in terms of molecular structure than that of the natural ester, therefore, if there are many cellulose particles, a large quantity of ‘weak links’ could be generated, resulting in the significant drop of dielectric strength. Furthermore, more ‘weak links’ could be generated easier with the increase of particle concentration even at a lower moisture content, so the moisture critical value decreases gradually as is indicated by the circle in the Figure 7.

V. CONCLUSION

Here come the conclusions drawn from the research above.

(1) When the moisture content of the natural ester is low (50 mg/L), the increase of cellulose particle contamination level from normal to high level can bring about a 25% reduction of the breakdown voltage. Besides, the particle content from normal to high level leads to a 45% drop of the breakdown voltage when the oil sample is relatively humid (450 mg/L). For the normal-level oil sample, the increase of moisture content from 50 mg/L to 450 mg/L causes a breakdown voltage reduction of 55%. And the moisture content rising from 50 mg/L to 450 mg/L leads to a breakdown voltage drop of around 60% for the high-level oil samples. With the combined effect of particle and moisture content, the breakdown voltage of natural ester can be decreased by 75%.

(2) Notable influences on relative dielectric constant and DC resistivity of the natural ester can be observed with the existence of cellulose particle and moisture, which may cause increase in the relative dielectric constant to a less extent and a decline in the DC resistivity to a greater extent as well. It can be inferred that cellulose particles and moisture affect the insulating properties by changing DC resistivity of the natural ester, thereby reducing the breakdown voltage.

(3) The difference of breakdown voltage between the DC and AC suggests the combined effect of particle and moisture and are determined by the physical and chemical properties of natural esters, cellulose particles and water.

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