Cellulose Particles' Effect on the Electrical Field Distribution Between Palm Oil and Mineral Oil Insulation Systems

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***Abstract*— The power transformer is one of the most important parts of the electrical network. The majority of high voltage transformers are filled with a liquid that functions as an electrical insulator as well as a heat transfer medium. An alternative that has been proposed is palm oil based oil which has a high potential to be used nowadays for the insulation of high voltage transformers. This study presents experimental results between palm oil (PO) and mineral oil (MO) on the influence of cellulose particles of transformer oil under AC voltage and its effect on the electric field distribution under AC electric field. When a voltage is applied to the oil with the cellulose particles, the particles begin to move across the electric field. The higher the AC voltage used, the greater the amount of particles that accumulate on the surface of the positive and negative electrodes. When the AC voltage reaches 25 kV for MO, cellulose particles appear to be merged in both electrodes. But for PO, the cellulose particles look unconnected in both electrodes due to the viscosity of the oil. The cellulose particles are observed to fully bridge when subjected to the 35 kV applied voltage. The electric field of the contaminated MO show higher values than those of the PO sample. This may be due to its higher viscosity than MO and causes the movement of cellulose particles in PO to be slower.**

Keywords—Transformer, dielectric insulating liquid, palm oil, mineral oil, cellulose particles, bridging

I. Introduction

Electrical insulating oils are an essential factor in the transmission and distribution of electrical power. The dielectric strength of insulating oils is influenced by particulate contamination. The adverse effect of particles has been recognized for a long time and often particles are considered as the source of failures in the large oil volume of HV transformers. The particle contamination causes a partial discharge in the insulating oil which in turn is indicative of a possible future breakdown in the system.

Oil acts as an electrical insulator and coolant and is in direct contact with metal, iron cores and paper insulation. So it is very easy to be contaminated. The particles in transformers come from various sources. During the manufacturing process, particles are left in the transformer tank either attached to the walls or on the winding surfaces. Contaminants such as metal filings or cellulose residue can form in the oil, especially for transformers with aged paper insulation. These contaminants tend to move towards high field areas due to the dielectrophoresis force (DEP) and can form bridges over a period of time [1][2]. The bridge can potentially act as a conducting path between two different potentials in the transformer structure, leading to partial discharge or insulation failure. Early work on cellulose particles has shown that the pre-breakdown phenomenon is closely related to the degree of contamination [2].

Although the oil filled into the transformers is usually filtered to remove impurities, the purified oil might be re-contaminated by residual particles. Therefore, a multiple filtering process is needed before a transformer goes through factory routine tests. During the operations, periodic inspections involving lids and covers being removed introduce dust and particles from the surrounding atmosphere to the transformer liquid. For in-service transformers, the cellulose materials continuously release particles into the liquid during the transformer ageing. Using spectroscopy and X-ray diffractions, experts have identified that iron, copper, carbon and cellulose fibre are the main constituents of particles for in-service transformers. The metallic particles are generally regarded as more dangerous than cellulose particles in dry oil. However, the detrimental effect of cellulose particles is more pronounced in the presence of water.

Cellulose particles are mainly come from paper insulating materials used in power transformers. Cellulose particles are polarized when the insulating liquid is stressed under an electric field, *E*. A polarized particle will eventually migrate to highly stressed area, such as electrode protrusions, and form cellulose chains, either partially or completely bridging the electrode. Consequently, as shown in Fig. 1, small cellulose particles might agglomerate into larger particles due to the polar components of the oil and the high surface energy of the particles [3][4]. The cellulose chains are generally recognized as partially conducting paths between the electrodes, favouring the liquid breakdowns. Therefore, the dielectric strength of mineral oil is significantly reduced in the presence of cellulose.

Fig. 1. The schematic of small cellulose particles aggregating into large particles [3]

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In recent years, some researchers studied the AC breakdown voltage with cellulose particles. A previous study by Wang [5] carried out an experimental study of AC breakdown voltage of ester liquid and mineral oil in the presence of cellulose particles. With the increase of cellulose particles, the results show that the AC breakdown voltage of ester liquid and mineral oil decreases. The presence of particles leading to a reduction in breakdown voltage is due to the promotion of the initiation of streamers in the liquid. In particular, Jian Hao et al. [6] has studied the effect of an electric field on bridging in natural esters and mineral oils under an AC electric field. They found that there is no bridge in mineral oil, which is contrary to the phenomenon of relatively thin bridge formation in natural esters below 25kV.

II. Experiment Description

A. Preparations of Oil Samples

In this study, two types of oil were used. The oils investigated are mineral oil (MO) and palm oil (PO) samples of Refined Bleached and Deodorized (RBDPO). MO is an unobstructed oil that complies with BS148 standards that is widely used in distribution transformers in Malaysia. RBDPO is obtained from cooking oil products available in the Malaysian market and this oil is processed through three filtering procedures namely degumming, bleaching and deodorizing. Pre-processing of samples is an important and necessary requirement before the testing can be done. The steps of sample preparation are illustrated in Fig. 2 according to the IEEE C57.637 standard [7].

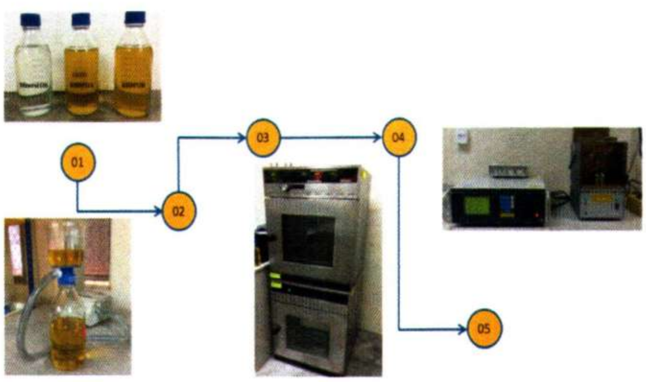

Fig. 2. Pre-processing of oil samples [8][9]

All oil samples were first filtered using a 0.2 μm pore size Thermo Fisher Nalgene membrane filter for at least three cycles to remove foreign particles in the oil sample. Next, the samples were put into a Memmert VO200 vacuum oven for drying (dehydration and degassing) at 85 °C for two days. Precautions must be taken during this process, the bottle must be opened to remove the moisture in the oil and only similar oil samples can be dried together in the oven at a time. This is to prevent the oil's characteristics from changing due to moisture absorption from other liquids.

Another 24 hours were given to the oil sample to cool to ambient temperature under vacuum conditions. An automated ADTR-2K Plus instrument was used to measure the dielectric parameters of MO and RBDPO. Specially designed oil test cells according to IEC and ASTM with a distance of 2 mm and pressure in the range of 100-1200 volts per mm will use. The parameters of the RBDPO and MO can be seen in Table 1.

TABLE I. The Parameters of Samples

Parameter	MO	RBDPO
Appearance	Transparent	Light Yellow
Dissipation Factor (90 °C)	1.32 %	4.85 %
Volume Resistivity (Ωm) at 90 °C	7.63×10^{15}	8.06×10^{12}
Relative permittivity (90 °C)	1.435	2.161
Viscosity, cSt at 40 °C	9.06	41.2
Saturated fat (g)	-	39.0
Poly-unsaturated fat (g)	-	10.4
Mono-unsaturated fat (g)	-	43
Vitamin E (mg)	-	47

Before use, the processed liquid sample should be in a closed glass container in a dry and clean condition. These two steps (filtering and drying) are important and crucial to minimise the impact of particles on the outcomes of the experiment. The particles content before and after the pre-processing process of the oil samples are shown in Table II. A HIAC ABS2 bottle sampler and a HIAC 8000A liquid particle counter particle size analyser were used to determine the particle content of the transformer liquid.

TABLE II. Particles Content Before and After the Pre-Processing Process of the Oil Samples

Oil sample	Particle Count					
	4 μm		6 μm		14 μm	
	Before	After	Before	After	Before	After
MO	234	222	47	25	5	2
RBDPO	522	267	44	27	4	2

The CIGRE working group 12.17 [10] were classified contamination levels only by only the amount of particles with a diameter greater than 5 μm per 100 ml. According to Table II, the processed oil samples after being purified, dehydrated and degassed are in good condition with particle number less than 500.

After all the samples were put through the liquid treatment process, all the particulate materials were dried in an oven at 105 °C for six hours and then cooled under vacuum for the next six hours. Finally, the processed liquid samples were artificially contaminated by particles and stirred for at least 15 minutes to ensure even distribution of particles in the liquid. In this research, the mess weight of iron, cellulose, and copper particles in powder form is 0.1 g, 0.5 g, and 1 g, respectively. All particulate materials were added to 100 mL of liquid resulting in three different volume concentrations, namely low (0.011%), medium (0.056%) and high (0.112%) [9].

B. Experiment on Bridging under AC Breakdown Voltage

The BAUR DTA 100C oil tester, as shown in Fig. 3, had been used to measure the breakdown voltages of the samples in this study. This unit has the advantage of being a totally automated system which increases the repeatability of the measurements. This unit can provide a maximum output of 100 kV.

For this study, two standard VDE (Verband Deutscher Electrotechniker) spherical electrodes with a 36 mm diameter opposite each other were placed in a transparent test cell as illustrated in Fig. 4. A gap distance of 2.5 mm between the electrodes is set according to the requirements of IEC 60156.

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The volume of oil tested is 400 ml. Based on IEC 60156, a continuous increase of 2 kV/s was applied to the test cell until the point of breakdown occurred. Each fraction is set to five minutes for RBDPO and two minutes for MO for each interim time. In order to guarantee an even distribution of particles between the gaps and ensure that the particles do not remain at the bottom of the test cell, a magnetic stirrer was used.

Fig. 3. AC breakdown test instrument for testing liquid dielectric breakdown [9]

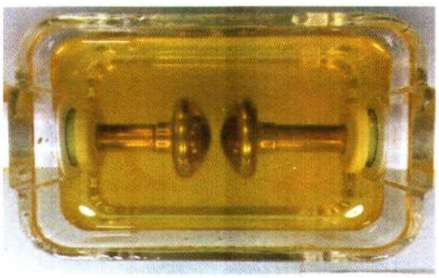


Fig. 4. VDE electrode configuration for the AC breakdown test [9]

C. *Effect of Cellulose Particles on Electric Field Distribution using ANSYS Software*

In this study, the phenomenon of cellulose particle aggregation and its effect on the distribution of the electric field in palm oil (RBDPO) and MO under an AC electric field is compared with an experimental study on bridging under AC breakdown voltage. The AC electric field simulation used a standard spherical VDE model in 2D axial symmetric as shown in Fig. 5 and the simulation parameters of MO and RBDPO contaminated with cellulose particles are described in Table III. These properties were obtained using the ADTR-2K Plus equipment.

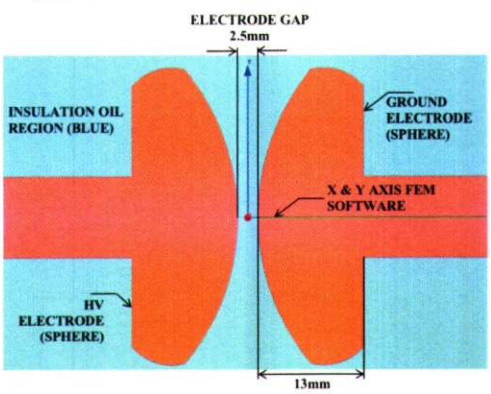


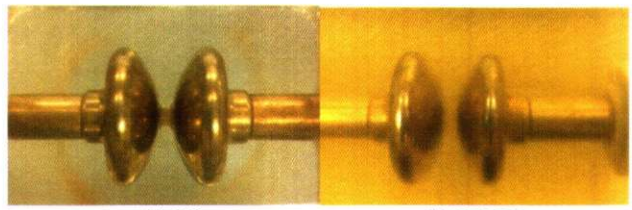
Fig. 5. VDE spherical model implemented in 2D axial symmetric to the actual test cell

TABLE III. CHARACTERISTICS OF MO AND RBDPO CONTAMINATED WITH CELLULOSE PARTICLES

Samples	Permittivity, ε_r	Resistivity, *R* (Ω.m)	Conductivity, σ (S/m)
MO	1.316	8.69×10^{11}	$1.1498e^{-12}$
RBDPO	1.854	2.24×10^{12}	$4.4723e^{-13}$

III. EXPERIMENTAL RESULTS AND DISCUSSION

When an AC voltage of 25 kV was applied, cellulose particles in MO and RBDPO were observed to accumulate gradually to the positive and negative electrodes. Fig. 6 and 7 shows the AC voltage of 25 kV and 35 kV below the breakdown voltage applied when the electrode distance is 2.5 mm to observe the bridging behaviour in mineral oil and RBDPO. As the AC voltage used gets higher, the amount of accumulated particles will be larger on the surface of the positive and negative electrodes. The particles are concentrated at the tip of the spherical VDE electrode on the positive and negative sides of MO and RBDPO. The figures show that in MO, the aggregated particles are dense, while for RBDPO, the aggregated particles are sparse.



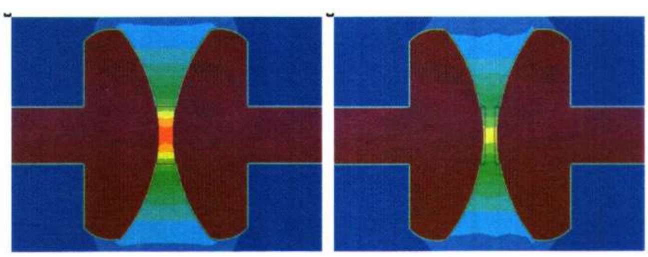
(a) MO (b) RBDPO

Fig. 6. Cellulose particles' accumulation at 25 kV

(a) MO (b) RBDPO

Fig. 7. Cellulose particles' accumulation at 35 kV

Fig. 8 shows the results of the electric field distribution calculated using ANSYS software under the simulation of a 25kV AC sinusoidal applied voltage. It can be seen that the cellulose particles adsorbed by the negative and positive electrodes under the AC electric field has a significant influence on the distribution of the electric field. When AC voltage reaches 25 kV for MO, cellulose particles appear to coalesce in negative and positive electrodes. But for RBDPO, cellulose particles appear to be disjoint in both electrodes due to the viscosity of the oil.



(a) MO (b) RBDPO

Fig. 8. Distribution of the electric field contaminated by the cellulose particles under an AC applied voltage of 25 kV

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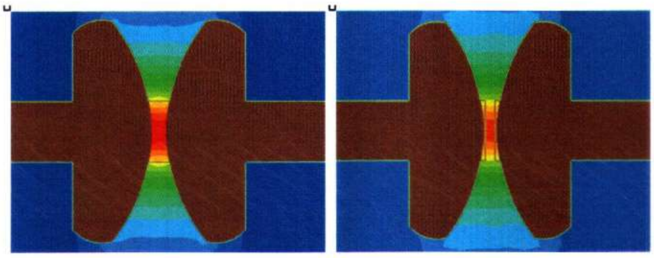
The cellulose particles are observed to fully bridge when subjected to the 35 kV applied voltage as shown in Fig. 9. Polarized particles will eventually move to highly stressed areas, such as electrode protrusions, and form cellulose chains, either partially or completely by bridging the electrodes. In MO, particles are adsorbed on negative and positive electrodes, while for the RBDPO sample, the migration speed of cellulose particles is much slower adsorbed on the VDE spherical electrode. Three factors can cause it to happen is due to the very light MO structure compared to RBDPO which has a higher viscosity. In AC, the electron moves to a high electric field takes a long time, so due to the MO structure, it is easy for the electron path to accelerate the breakdown process. Cellulose particles will fall faster than MO after breakdown occurs with the viscosity of RBDPO. The second factor, this phenomenon may be related to oil and particle conductivity. The conductivity of the contaminated insulating oil will increase with the increase in the content of cellulose particles. Thirdly, the relative permittivity describes the ability to polarise materials subjected to an electrical field. A higher realtive permittivity value of RBDPO allows more charge to be stored in the dielectric fluid. This can reduce the electric field stress mismatch between the solid insulator and the liquid to achieve higher resistive field strength.



(a) MO (b) RBDPO

Fig. 9. The electric field distribution contaminated by cellulose particles under an AC applied voltage of 35 kV

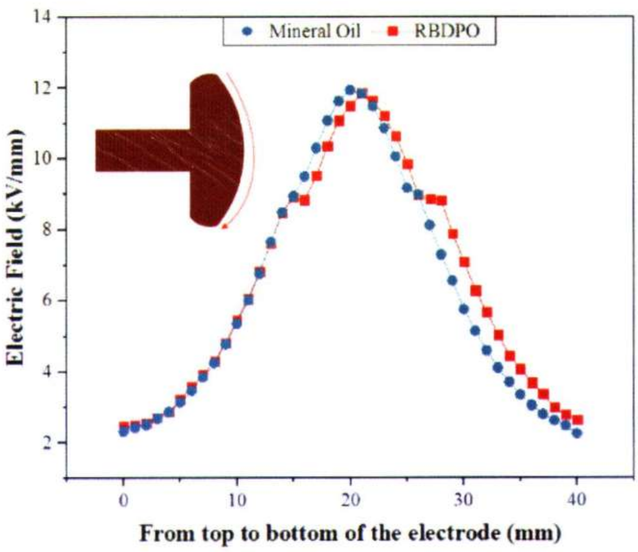


Fig. 10. Electric field distribution from the top of the VDE spherical electrode to the bottom of the electrode

As shown in Fig. 10, the electric field strength at the tip of the mushroom shape is maximum in MO and RBDPO samples. The field intensity near the VDE spherical electrode can be reduced by fibre particle adsorption. The maximum electric field strength that appears at the edge of the particle in MO is slightly higher than the value in RBDPO as the field strength increases in the middle of the electrode surface. Under an AC electric field, the electrode has a significant influence on the distribution of the electric field when the cellulose particles are absorbed. The field intensity near the VDE spherical electrode decreased, however, the field strength in the central region of the electrode increased. In the case of particles adsorbed on the electrode surface, the maximum electric field strength appearing at the particle edge in MO is slightly higher than the value in RBDPO.

As a result, the cellulose particles will be moved, inducing more charge and collected in areas of high electric field. It will form a "weak link" or "Impurity Bridge" between oil gaps to initiate breakdown and increase the local electric field. As the applied voltage and cellulose particles increase in RBDPO and MO, the probability of breakdown will increase due to more weak links being formed, thereby reducing the breakdown voltage. The electric field of the contaminated MO shows a higher value than that of the RBDPO sample. This may be due to its higher viscosity than MO which causes the movement of cellulose particles in RBDPO to be slower. The slow movement of cellulose particles in RBDPO will stop the development of "Impurity Bridges" and reduce the incidence of breakdown. Similar findings regarding the dependence of viscosity and breakdown voltage have also been reported in [11][5][12]. In addition, the high viscosity of RBDPO can reduce the movement of charge carriers and prevent the creation of gas bubbles in the oil.

IV. Conclusions

Under AC electric field, no matter in MO or RBDPO, the movement velocity of cellulose particles plus bridging is faster and the thickness of the bridge increases with increasing voltage. However, a greater number of particles accumulated in MO than in RBDPO, on the surface of positive and negative electrodes, which proves the better insulation property of RBDPO. In RBDPO, a quite thin bridge is found under 25 kV. However, in MO, the rate particle accumulation shows a form of "weak link" or "impurity bridge" across the oil gap and complete the bridges. Cellulose particles adsorbed by the electrode have a significant influence on the distribution of the electric field. Therefore, it can be concluded that palm oil has good potential to be developed as an alternative power transformer oil. Hence, considering the economic, environmental and social costs, the uses of palm oil for Malaysia should become a viable option.

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