Experimental Studies of Influence of Different Electrodes on Bridging in Contaminated Transformer Oil

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ABSTRACT

Contaminated transformer oil has been tested under non uniform electric fields and the effect of different electrode systems presented in this paper. Three different electric fields were examined i.e. DC, AC and DC biased AC. These experiments revealed that with all the different electrodes arrangements, contaminated particles always formed bridges between electrodes under DC electric field. The bridges were thicker and more particles were attracted with more uniform electric field (spherical electrode) than with a divergent electric field (needle-plane).

Index Terms - **HVDC transformer, failure, contamination, Dielectrophoresis, drag force, bridging.**

1 INTRODUCTION

POWER transformers are one of the most important components in high voltage transmission and distribution systems. Reliable operation of this equipment is utmost priority to energy generation sectors and end users. Replacement rates of these transformers have started to accelerate as more of them are reaching or beyond their designed lifetime. It has been previously reported [1] that almost one third of total transformer failures are caused by insulation failures. To prevent failures it is therefore important to understand failure mechanisms [2].

Liquid dielectric oil is used in many high voltage applications including almost all high voltage power transformers. Transformer oil serves two very important purposes, not only it works as an electrical insulation but also as a heat transfer medium. Like many other liquid dielectrics, it also has some disadvantages; one potential problem is contamination [3, 4], which deteriorates its electrical performance. Dielectric liquid inside a transformer is usually in contact with metal, iron core and pressboard insulation. Metal filings or cellulosic pressboard residual can be formed in transformer oil, especially for aged transformers with old pressboard insulation. In addition, due to its complicated structure, a strong non-uniform field is present within various areas of a transformer. During operating condition the contaminant particles may get charged and tend to move towards high electric field gradient regions due to the dielectrophoretic (DEP) force [5]. These contaminant particles can form a bridge over a period of time. The bridge may lead to partial discharges or total insulation failure.

Demand for HVDC transformers has increased as renewable energy sources like off-shore wind farm and more long distance DC transmission lines are to be built to meet energy requirements for 21st century [6, 7]. Some parts of these HVDC converter transformers experience the combined effect of AC and DC electric fields [8]. Previously conduction current, partial discharges, resistivity [9-13] of bridging in transformer oil with DC and AC electric fields have been studied. Effects of particle size and mathematical modelling of bridging have been previously reported [14, 15]. Considering the presence of non-uniform electric field inside a power transformer, our current work focuses on the effect of strong non-uniformity of electric field on bridging. Shape of the electrodes also play a vital role on breakdown voltage [16]. Some of our results from electrode shape and paper barrier was reported in [17, 18]. The combined DC and AC voltage has been applied to investigate the dynamics of contaminating particles. The results have been discussed in comparison with phenomena observed with spherical electrodes. The paper starts with experimental analysis of DC conditions, and then extends the tests to sinusoidal AC voltage. Finally, the combined effects of DC biased AC electric field are presented to simulate the behaviour of real HVDC transformer. Three different experiments have been performed to investigate the particle accumulation between two electrodes with different potentials under DC, AC and DC biased AC voltages. The effects of different level of contaminations ranging from 0.001 to 0.024% by weight were also accomplished along with three voltage levels for each

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voltage category. Optical microscopic images of pressboard particle accumulation and conduction current were recorded during experiments for DC and AC electric field.

2 EXPERIMENTS

2.1 SAMPLE TANK AND ELECTRODES

A purpose built glass sample tank was used for all the experiments and the total volume of this tank was 550 ml. Two different electrode systems, i.e. sphere-sphere electrodes and needle-plane electrode system were used.

The spherical electrodes were made of brass with a diameter of 13 mm. The needle electrode is made of tungsten and it was produced in our laboratory from a tungsten wire. Chemical etching technique was used to make the needle shape. The body of the needle is 1 mm of diameter and the slope of the tip started from about 5 mm above. The tip of the needle is approximately 100 µm of diameter. The material of plane electrode is brass and it has a diameter of 50 mm with a thickness of 5 mm. The edge of the plane electrode was rounded to avoid electric field enhancement.

For both electrode systems mentioned above, the electrodes were attached to either side of the test cell wall from which they extended towards the middle of the cell. One of the electrodes was positioned to the wall and another electrode could be moved using a screw drive. The distance between the electrodes from both electrode systems were kept constant at 10 mm for all the experiments reported here.

2.2 SAMPLE PREPARATION

Cellulose fibre dust was produced by rubbing a piece of new pressboard typically used in high voltage transformer by metal files with different cut sizes. Different sizes of sieves were used afterwards to separate the fibres. As a result, the particles were separated by the fibre width rather than length. The particles were categorized into four different sizes i.e. 250-500 µm, 150-250 µm, 63-150 µm and less than 63 µm. All the four sizes of particles were tested under DC electric field. All these 4 cases show a consistent behaviour and only the results from 150-250 µm and 250-500 µm tests are discussed in this paper (the smaller the particle the quicker the bridging). Only 63-150 µm size particles were investigated for AC and DC biased AC experiments, with smaller size chosen to enhance the bridging. The contamination levels for each size of particles were 0.001, 0.002, 0.003, 0.004, 0.006, 0.008, 0.016 and 0.024% by weight. A digital measurement scale capable of measuring microgram was used to achieve the better accuracy. For DC experiments only 0.001% to 0.004% contamination levels were investigated whereas for AC all the above contamination levels were used. In the case of DC biased AC, only 0.024% which was the highest contamination level was tested along with a pure 3 kV DC voltage.

The sample tank was cleaned with a soap solution in hot water then it was dried in hot air flow before starting a new test with a new size of particle. When repeating a test with same particle size, the sample tank was first rinsed with clean oil then the test cell was rinsed thoroughly with cyclohexene.

A new experiment was always started with adding 300 ml of transformer mineral oil into the test cell which was enough to submerge the electrodes completely under oil. The lowest contamination level of pressboard fibres was then added to the oil. The test cell was covered with cling film to protect from dust and moisture. The sample tank was covered during whole experimental period apart from adding the next level of contaminants. The sample tank was stirred prior to every test on a magnetic stirrer for 2 minutes to disperse the particles evenly.

2.3 EXPERIMENTAL SETUP

The sample tank was positioned under a stereo microscope that had a digital camera mounted on the top to record optical images of the particles accumulation. For experiments with DC electric field, the microscope along with the test cell was placed inside an aluminium box which acts as a Faraday cage to reduce a possible noise in measurements of the conduction current. As for AC and DC biased AC test the aluminium box was not used. One of the spherical electrodes was attached to the high voltage source. The other electrode was connected to the ground via a Keithley picoammeter 6485 (DC) and Keithley multimeter 2001 (AC) to measure the conduction current through the gap. The conduction current was not measured for DC biased AC test so the electrode was directly attached to ground. A desktop computer was used to control the digital camera, to collect data from the camera, and also for the conduction current measurement.

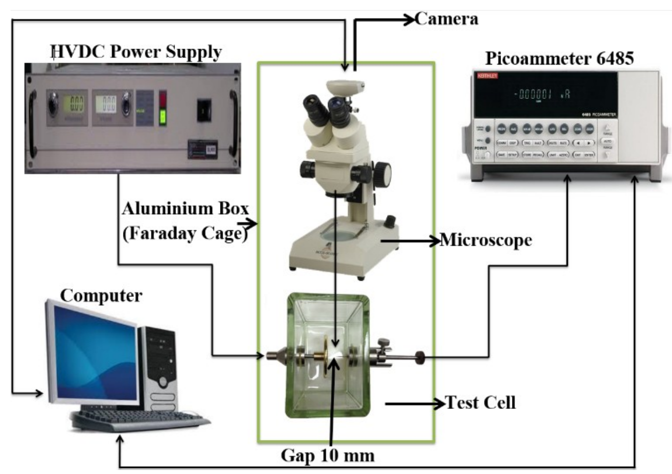

Figure 1. Experimental setup for DC test with needle-plane electrode system.

A block diagram of complete experimental setup for DC tests with needle-plane electrodes is shown in Figure 1. A detail description of DC experiments can be found in [14]. This experimental setup for DC biased AC test consisted of a signal generator, high voltage amplifier, sample tank/test cell, microscope, digital camera and computer. A signal generator was used to produce the sinusoidal voltage of 50 Hz with a DC offset. This signal was amplified with the high voltage amplifier from TREK, Inc. The ratio of the amplification was 2000:1. The amplified signal was send to one electrode. The high voltage amplifier was also connected to an oscilloscope and the output voltage was monitored. The other electrode was connected to the ground.

Three different voltage levels were investigated for each category of voltages, such as DC (2, 7.5 and 15 kV), AC (10, 15 and 20 kV peak-to-peak with a constant frequency of 50 Hz) and DC biased AC (1, 3 and 6 kV DC offset with 10, 15 and 20 kV AC peak-to-peak with a constant frequency of 50 Hz). Each experiment was carried out until a complete bridge was created between the electrodes or maximum of 25 minutes where there was no bridge. A stereo microscope from GX Optical, model XTL3, equipped with GXCAM-1.3 digital camera to record images and videos was used. Images were taken in a regular interval during the entire test to record the bridging process along with some videos. All tests were conducted at ambient room temperature. All the tests were conducted three times for each voltage level to observe the repeatability of the obtained results.

3 RESULTS AND DISCUSSION

3.1 DC TEST

The images obtained from the experiments using two different electrode systems are shown in Figure 2 and Figure 4. Applied voltages for the experiments with spherical electrodes were 2, 7.5 and 15 kV with a concentration level of 0.003%. For needle-plane electrodes systems, the applied voltages were 1, 3 and 6 kV and cellulose particle contamination level was 0.016%. The particles' sizes for both of these experiments were 150 – 250 µm. It has been observed that pressboard particles started moving between the electrodes upon the voltage application. The reason behind the movement of particles could be explained in the following way. As soon as the power is applied to the system, under DC electric field the particles start to become polarized. The fibres then align themselves parallel to electric field lines. Due to non-uniform electric field, the particles experience DEP force [5] and the fibres move towards the electrodes. Once the particles touch the electrode surface they acquire charges from the electrode. When the charge transferred to a fibre reaches a certain level and the repelling Coulomb force acting on the fibre is greater than the attractive DEP force, the particle gets off the electrode surface and travel towards opposite electrode under a combined action of the Coulomb force, DEP force and the drag force from viscous oil. At this stage the motion is mainly controlled by a balance between Coulomb and drag forces since DEP is relatively weak. The particle finally reaches to the opposite electrode, where it discharges and acquires charge of different polarity. The dielectric particles travel back and forth from one electrode to the other in this fashion. Under such motion the particles generate more or less steady current with the current value depend on applied voltage. The DEP force pushes particles towards high field regions near electrodes and they start to accumulate between the spherical electrodes. A detailed explanation of the mechanism of bridging under DC electric field can be found in our previous report [19].

After applying 2 kV there was a noticeable shallow bridge created after 600 s for spherical electrodes as shown in Figure 2. A few different branches were attached from one electrode to the other. Note that a complete thin bridge was created within 180s in this case.

For 7.5 kV applied to spherical electrodes, a thin bridge formed after 10 s. The bridge was continued to thicken until 300 s (Figure 2). No changes of bridge formation were observed after that.

After applying 15 kV, similar qualitative observations were made. A thin complete bridge was made within 5 s, and the bridge was thickened up to 60 s.

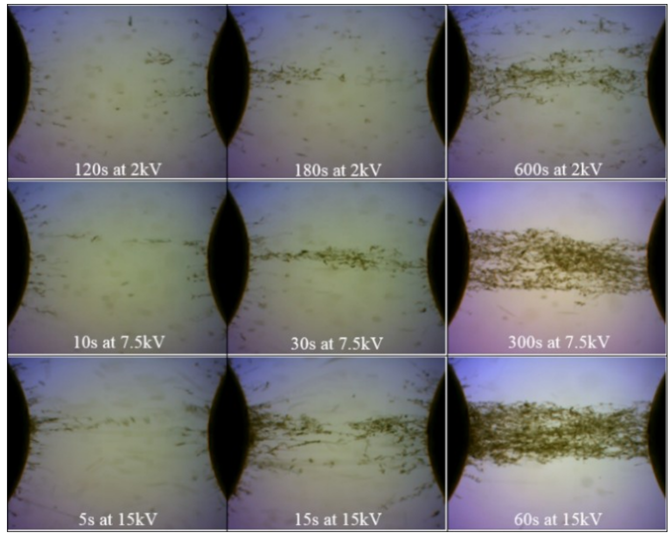

Figure 2. Optical microscopic images of bridging in contaminated transformer oil with 150-250 µm pressboard fibre using sphere-sphere electrodes, concentration level 0.003%.

To explain the observed behavior, the DEP force has been simulated using COMSOL software [20]. The simulation used axisymmetric 2D geometry and electrostatics module to calculate the electric field. DEP force calculated from the equation,

$$F_{DEP} = 2\pi r_p^{\,3}\varepsilon_0 Re(\varepsilon_f^{\,*})Re(K)\nabla E^{\,2} \qquad (1)$$

where, r_p is particle radius, ε_0 is permittivity of vacuum, $\varepsilon_f^{\,*}$ is complex permittivity of the oil $\varepsilon_f^{\,*} = \varepsilon_f - j\frac{\sigma_f}{\omega}$, $\varepsilon_p^{\,*}$ is complex permittivity of particle $\varepsilon_p^{\,*} = \varepsilon_p - j\frac{\sigma_p}{\omega}$, K is Clausius - Mossetti factor $K = \frac{\varepsilon_p^{\,*}-\varepsilon_f^{\,*}}{\varepsilon_p^{\,*}+2\varepsilon_f^{\,*}}$. In this study the only variable parameter is applied voltage and associated electric field E. As seen from equation (1) different experiment would represent effects of grad(E^2) which have been studied for different electrodes' arrangements.

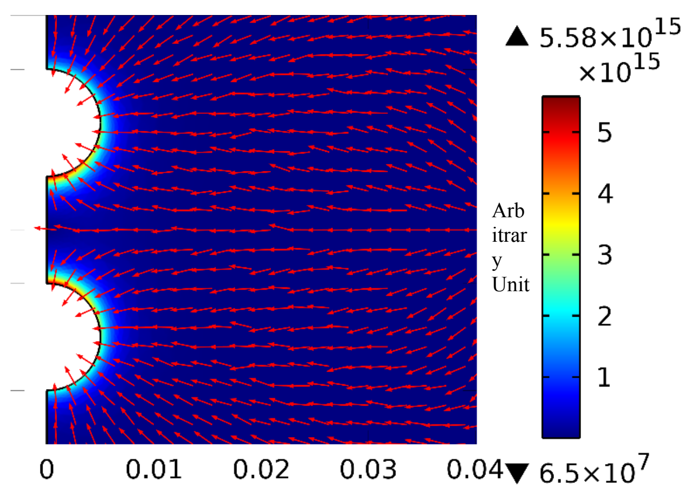

Figure 3. Simulation of electric field for spherical electrode system. The color surface represents the intensity of the gradient the electric field squared. The red arrows point towards the direction of the force.

The simulation result from spherical electrode system is shown in Figure 3. The DEF is significant near the large surface area of the electrodes and the fibres would be attracted to these points on the surface. The arrow indicates the direction of the force acting on the particles. Under DEF force the particles should accumulate from either side of the electrodes, but their motion is not directed straight towards the electrodes. Many particles move first towards the central line between the spherical electrodes and near this line they turn toward the electrodes. Such behavior explains the bridging dynamics on Figure 2.

To summarize the observations in the case of needle – plane system, it can be noted that the physical process taking place are similar to the case of spherical electrodes. But the fields are different and it reflects in the results. The particles were first polarized due to the DC electric field. Because of the gradient of the electric filed the particles were experienced dielectrophoretic force and they started to draw close towards high electric field gradient region at the needle tip. Then the particles were charged from the one electrode and discharging on the other side. The charging time is almost instantaneous on the needle tip and the particles travel very fast when they were travelling from needle towards the plane. But it takes much longer time for the particles to gather charge from plane electrode and they also travel much slower from plane towards needle. Once the particles get close to the needle electrode about quarter of the gap distance, the particles move faster to the needle. The spherical and fibre particles were attaching themselves to both electrodes, although both DEP and Coulomb forces are much higher near to the needle tip. The initial bridging process always started from the long fibre particles. The fibres attached to the both electrodes and align themselves parallel to the electric field lines. Then the spherical/small particles attached to the long fibres and some more fibre attached to the end of the initial fibres. This process continues until they form a full bridge between the electrodes.

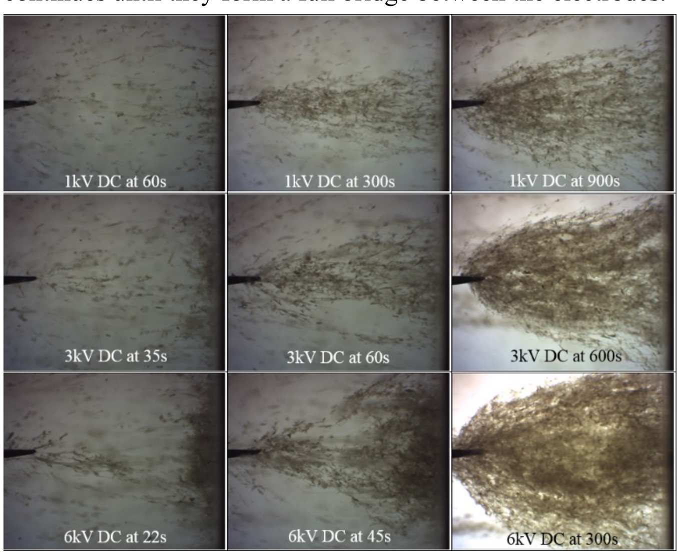

Figure 4. Optical microscopic images of bridging in contaminated transformer oil with 150-250 µm pressboard fibre using needle-plane electrodes, concentration level 0.016%.

There were some pressboard particles attached to the needle electrode after 60 s of the 1 kV power supply turned on. There was thin bridge formed within 300 s. There was no noticeable change to the bridge observed after 900 s for the needle-plane electrode system as shown in Figure 4.

The particles movements were increased with the applied voltage of 3 kV. Particles were accumulated towards the electrodes and started to attach themselves within 35 seconds of the power supply started. There were a few branches of the bridge formed within 60 s. The bridge was continued to grow until 600 s. The bridge for 3 kV supply was shallow.

The bridging process increased dramatically with applied voltage of 6 kV. Within few seconds of starting the test, the particles were attaching themselves to form the bridge. One or two branches of the bridge formed as soon as 22 s. The bridge was forming until 300 s thereafter there was no change occurred. The bridge was more compact than 3 kV. The bonding between the branches was stronger than the previous one because of the stronger electric field.

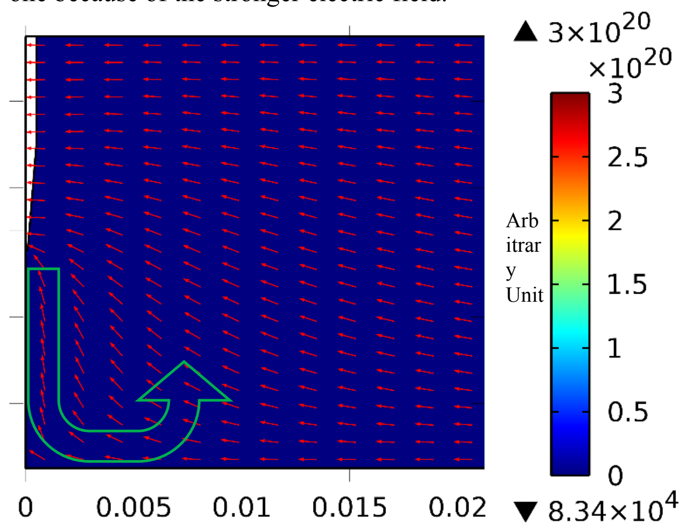

Figure 5. Simulation of electric field gradient for needle-plane system. The color surface represents the intensity of the gradient of electric field squared. The red arrows point towards the direction of the force. The green arrows indicate qualitatively the convective oil flow introduced by charge injection in strong electric field according to [21].

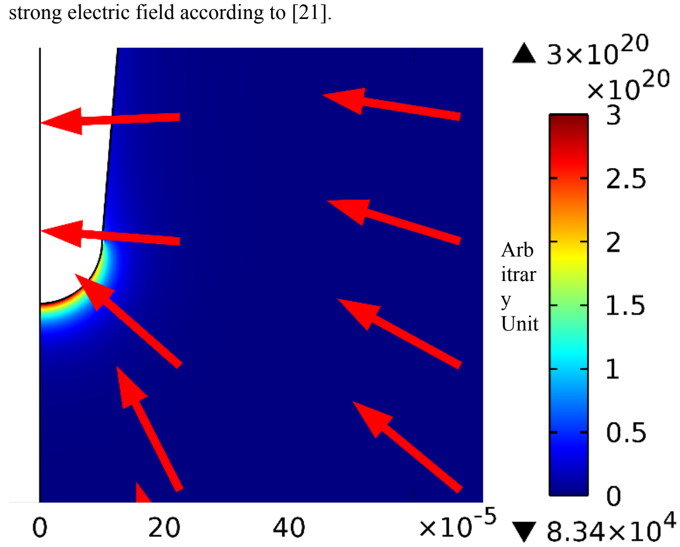

Figure 6. The zoom in view of the needle electrode. The notations are similar to **Figure** 5.

The electric field distribution for needle plane electrode system is shown in Figure 5. Again, the particle will tend to move towards the electrode, but they are still attracted to the central line between the needle and the plane. So the bride grows slowly from the needle. At low voltage there is no particles' accumulation at the plane electrode, but as voltage increases the particles can be seen at the plane surface as well. It can be attributed to electro convective flow. There is a charge injection to the particles from the needle which force them to move under combined action of Column, DEP and the drag force. The drag force is large in the vicinity of the needle but weak near the plane electrode.

The close view of the needle electrode in Figure 6 indicates that the DEP force is really small in the oil volume except the region next to the needle tip. It means that even if the particles are attracted to the needle they can be easily swept away by electro-convective flow at high voltages. On the other hand the convective flow is not strong in the vicinity of the plane electrode and it explains an accumulation of the particles at the plane electrodes for high voltages, Figure 4.

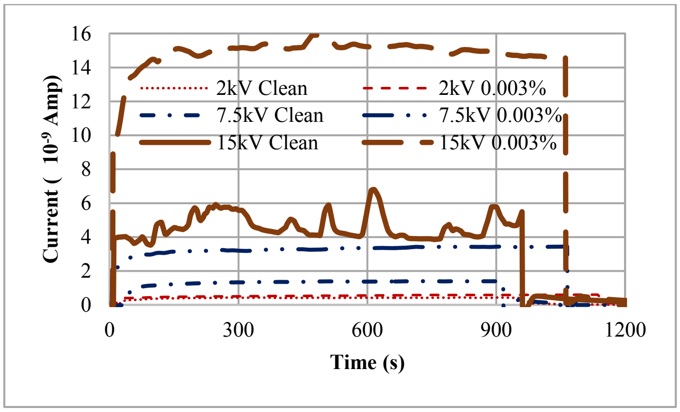

Figure 7. Conduction current at different voltages using sphere-sphere electrodes with clean and 0.003% contaminated transformer oil.

The conduction current for spherical electrode system under the influence of three different voltage levels are shown in Figure 7. There was a high polarization current observed in most of the experiments almost instantly after the voltage was applied. After that the slow growing current was established. The existing of the current can be explained by charging of the particles at the electrodes and transfer the charge across even if the bridge is not formed yet. Then the currents were gradually increased until a complete thick bridge formed. It is clear based on current results that charge transportation is taking place by the pressboard particles under DC electric field. Conduction current under low electric field (E<0.44 kV/mm) is directly proportional to the electric field E is proportional to electric field [22]. But under high electric field (E> 1.33 kV/mm) the conductive current is proportional to V^2 that can be explained by space charge limited electron current through oil [22, 23]. In the experiments with spherical electrodes the low field exist for 2 kV applied voltage, whereas 7.5 and 15 kV cases correspond to high field case. And in Figure 7 the current is initially proportional to voltage but it starts to rise as V^2 at higher voltages. The conduction current for contaminated oil was always higher than the clean oil. It was about two times and four times higher than clean oil under 7.5 and 15 kV respectively.

Similarly there was a high polarization current observed as soon as the power supply turned on for needle-plane electrodes (Figure 8) for most of the experiments. Then the current was dropped slightly and a slow increase of current was observed for 1 and 3 kV clean oil. There was a sudden high current observed for clean oil under 6 kV due to partial discharge. Conduction currents for all voltage levels had slow increment and they settled when they reached saturation point after a while. It is worth to note that for the case of spherical electrodes the "steady" current is approximately proportional to voltage squared at high voltage, but for needle-plane case the dependence is more complex. In latter case the strong field exist in the vicinity of the needle even for low voltages. But the large volume of oil is still under the low field. That why the current is approximately linear for the needle-plane system. The presence of the near needle region gives some non-linear rise in the current as can be seen for 6 kV case in Figure 8. The conduction current for contaminated oil was always higher than the clean oil for needle plan electrodes as well. The value of the currents were three times and five times higher than clean oil under 3 and 6 kV respectively.

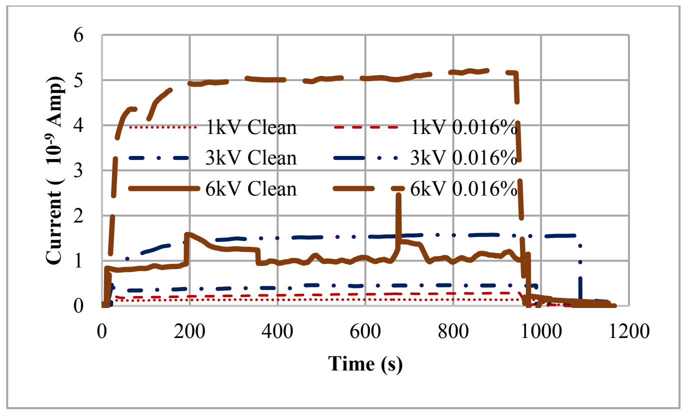

Figure 8. Conduction current at different voltages using needle-plane electrodes with clean and 0.016% contaminated transformer oil.

3.2 AC TEST

Several contamination levels i.e. 0.001, 0.002, 0.003, 0.006, 0.008, 0.016 and 0.024% were tested under influence of 10, 15 and 20 kV AC applied voltage on spherical electrodes. The pressboard particles started moving slowly when the 10 kV AC supply was applied. As time elapsed, particles were attached to both electrodes evenly, as shown in Figure 9. The particles accumulation on the electrodes surface amplifies with increment of both voltage and contamination levels. A complete bridge between the two electrodes was never created opposite to the DC experiments because of the alternating polarity of the applied voltage. The particles cannot leave the surface of the electrodes because of alternating Coulomb force (DEP force always pushes particles towards electrodes). These results are similar to previously reported [13] except previous report [10] where the bridging was observed between spherical electrodes. From our experiments we have found out that the texts are really sensitive to experimental condition and sample preparation. If the contaminated oil sample are tested under the influence of DC electric field then the sample tested under AC electric field, there will be bridge formation under this specific condition. It is possible that in [10] the high voltage AC source might have introduced a DC offset and it let to the bridge formation. Although the experiments [10] used lower voltage, 6 kV, they were done in moistened transformer oil which may affect DEP force. Moisture will affect the conductivity of the pressboard so the DEP force will also change as the conductivity ratio between the oil and pressboard will change. Moreover the particles will need less time to charge as well as the amount of charge they will get from the electrode is also depends on the conductivity of the cellulose particles. All these factors may result in significant increase of DEP force and even small DC offset may lead to the bridge formation.

The electric current under AC test was measured to be about 6 mA for 15 kV AC voltage. The current did not change significantly for any contamination levels from 0.001 up to 0.024%. This is what was expected, since the observed current is dominated by the displacement current which is 6 orders of magnitude higher than conduction current in DC case, Figure 7. Since complete bridge between the electrodes under AC electric field has never formed, the current stays at constant level. In fact the conduction current due to charge transport in this case would be even smaller compared to DC case. To transfer charge from the electrode to the particles, certain amount of time is required to accumulate sufficient amount charge so the repelling force can lift particles off the electrodes. It is expected that in AC case the charge passed during a short half-cycle is small and only a fraction of a charged fibres can be detached from the electrodes by Coulomb force. But even these fibres are attracted back to the electrodes at the next half-cycle.

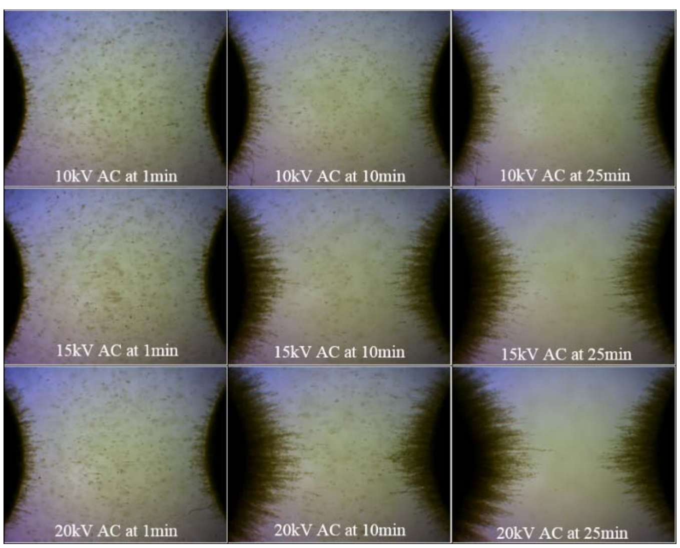

Figure 9. Optical microscopic image for bridging under influence of AC electric field with 0.024% concentration of 63-150 µm cellulose particles.

For the needle-plane system the AC voltage was slowly increased to desired level of 5 kV. Images from the needle-plane electrode system under AC electric field are shown in Figure 10. The particles were started to move slowly towards the high electric field gradient region because of the DEP force. They started to gather mainly on the needle tip but some of them were going towards the plane electrode. After 1 minute there were some particles observed on the tip of the needle and not many particles attached to the plane electrode. As time progressed more particles accumulated on the needle tip until 25 min thereafter there was no apparent change taken place. There were a small number of particles attached to the plane for the 5 kV testing voltage.

The particle accumulation dynamics were changed for higher electric field of 10 kV AC. The particles were started to move from the needle towards the plane electrode. They were shooting to the plane electrode then after hitting the plane electrode, some of them attached to the plane and others were moving away from the plane electrode. The motion of the particles was consistent with electro-convective flow due to charge injection into a dielectric liquid [24]. In this case the high electric field creates two turbulence waves propagating from the needle to the plane and returning back at the sides [25]. In dielectric liquids, space charges (ions) are mainly created by two mechanisms: one is the dissociation and recombination phenomenon [26], the other one is the charge injection [27]. It has been demonstrated that in blade plane geometry the dissociation/recombination phenomenon induces a flow from plane to blade [28-30] while liquid flows in the opposite direction when an injection occurs [21, 31]. In our experiment there were very few particles accumulated at the very beginning of the test but later on all the particles were attached to the plane which is completely opposite of what was observed for 5 kV. It suggests that there were charge injected to the oil at the needle and the oil moves towards the plane dragging the fibre particle. To explain completely different regions for the observed fibre accumulation at 5 and 10 kV we have to assume that the charge injection is only noticeable at voltages above 10 kV. The particles accumulated on the surface of plane electrode experience a combination of DEP force and the drag force due the oil flow. These forces are low at the surface of the plane electrode and the particles were stuck on the surface. Similar phenomenon was observed for 15 kV.

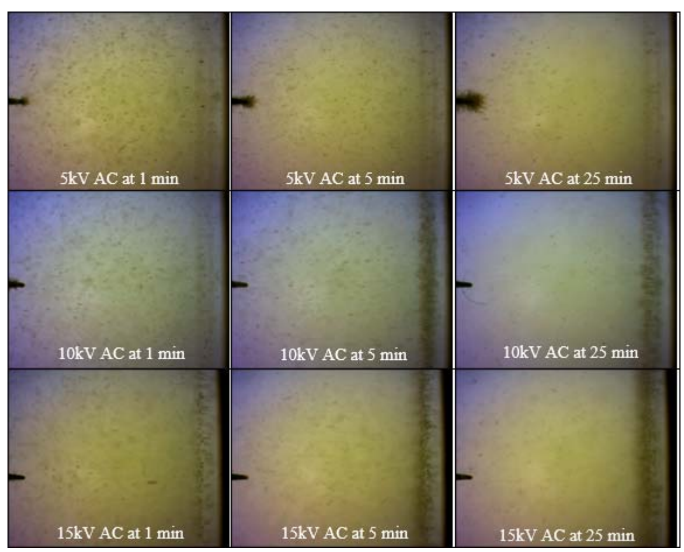

Figure 10. Optical microscopic image for bridging under influence of AC electric field with 0.024% concentration of 63-150 µm cellulose particles.

Taking into account observation described in the previous section, AC produces unexpected results for needle-plane system. DEP force is proportional to voltage squared whereas electro convective force (velocity) linearly depends on voltage for blade electrodes [21]. So accumulation of fibres is expected at the needle tip as the voltage increases. The opposite behaviour is observed. It may be explained by exponential increase in charge injected into the oil with increase of the voltage for our experiment.

3.3 DC BIASED AC TEST

Three different DC offset levels were investigated i.e. 1, 3 and 6 kV for both electrodes systems. The AC voltage of 10 and 15 kV for the spherical electrodes and 5, 7 and 10 kV for needle-plane electrodes were imposed over the DC bias.

All of these three levels of DC voltage showed that as the AC voltage increased, the thickness of the bridge also increases for spherical electrodes. Figure 11 shows a comparison of 3 kV DC electric field over imposed on different AC loads. It visualizes the difference in bridging dynamics as a function of the AC load. There are many branches of the bridge which were formed within 30 s after the 3 kV DC supply was switched on. The thick bridge was formed over a period of 15 min but it was a shallow bridge with lots of different branches. When the 3 kV DC was combined with 10 kV AC, a very thin bridge was created after 20 minutes and with many pressboard particles are attached to both electrodes. For 15 kV AC, a complete bridge formed between the electrodes after 10 minutes and 5 minutes respectively. So the particle accumulation and bridging process is much slower in comparison to pure DC electric field although the bridge density is much higher.

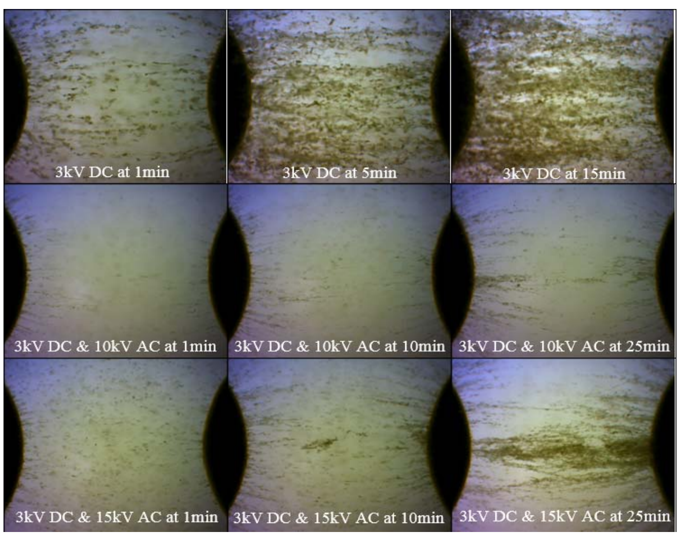

Figure 11. Increment of pixels in microscopic images under influence of DC biased AC electric field with 0.024% concentration.

To form the bridge the particles have to travel towards the central line between the electrodes. But DEP pushes the fibre's to the electrodes surfaces. So first particles travels to the electrodes, get a charge, are detached from the surface, move towards the opposite electrode by Coulomb force and be pushed towards the central line by DEP. It is the DC voltage which dictates the average value of Coulomb force, whereas RMS of DC+AC combination affects DEP force. It means the addition of AC component forces the fibre's to stick to the electrodes stronger and only a fraction of fibre's can travel between electrodes. So it takes longer for the same number of "active", highly charged fibre's to move between the electrodes. As the result the bridging dynamics is much slower. But the DEP force is much stronger with AC addition; it pushes fibres to the central line stronger and makes the bridge much denser. The particles chains which are on either side of the electrodes operate as conductive extensions of the electrodes with new fibre's are attracted to ends of these chains. It creates the bridge in the centre although many incomplete branches can grow on the electrodes surfaces.

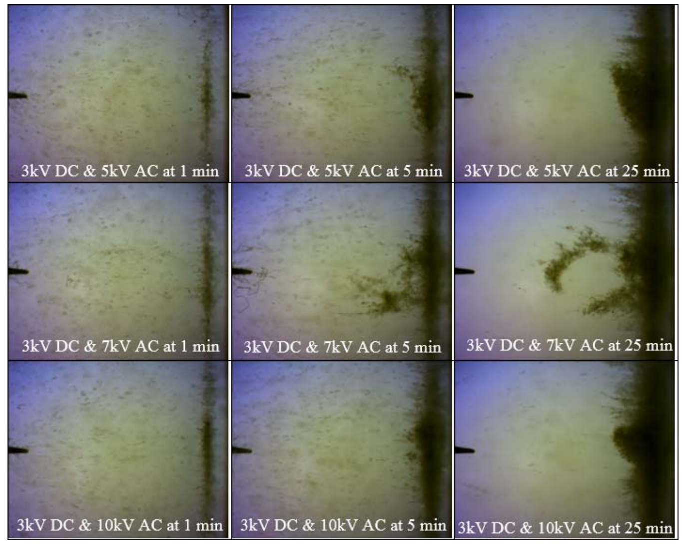

Figure 12. Optical microscopic image for bridging under influence of DC biased AC electric field with 0.024% concentration of cellulose particles.

There were three different levels of AC voltages i.e. 5, 7 and 10 kV were used with a DC offset of 3 kV for needle-plate system and the images from these tests are shown in Figure 12. The particles were started to detach and move from the needle to the plane electrode after the 3 kV DC biased 5 kV AC was applied. They accumulated on the both electrodes initially. As time progressed there were more particles attached to the plane than the needle tip. At the end of 25 min all the particles left the needle tip as it was observed on AC test. Taking into account observation described in previous sections, AC+DC combination produces results similar to AC case for needle-plane system. Strong electro convective force does not allow particles to stay at the needle tip, they are pushed towards the plane electrode. But this time more particles were attached to the plane electrode than pure AC test. So the effect of DC was to accumulate more particles to the plane electrode.

4 CONCLUSION

To our knowledge, the effect of the combined DC and AC electric field on bridging in contaminated transformer oil has been studied first time. Such a study is timely considering the renewed interested in HVDC power transmission. From the above results and discussion, the following conclusions can be drawn.

There are differences in bridging shape and the amount of force acting on the particles due to difference in shape of electrodes. The bridge is thick and strongly bonded for gradually changing electric field between spherical electrodes under DC load. On the other hand a shallow bridge is formed for needle-plane electrodes system under similar DC load. In the first case DEP force is high enough over a large volume of oil, which is strong enough to push the particles into the region between the spherical electrodes. But for the needle-plane system the force is very strong near the needle tip, but become very weak as the particles move towards plane electrode. So the particles travel along the field lines without being concentrated near the central line connecting two electrodes.

For AC load, surface of spherical electrodes always exposed to a very strong DEP force acting on the particles, which brings more the particles to the electrode surfaces and not allows fibre's to move away. But for needle-plane electrode system, the DEP force at lower voltage attracts the particles only towards the needle electrode and not towards the plane electrode according to the direction of the electric field gradient. When the voltage increases, the needle electrode inject electric charge into the oil which induced an electro convective force in the liquid towards the plane electrode. The flow of the oil drags cellulose particles to the plane electrode and fixes them on it.

High electric field for DC biased AC load produces large charge injection into the oil. As a result very few particles were attached to the needle due to DEP force. Majority of the particles were swept by the fluid flow and pushed back towards the plane electrode.

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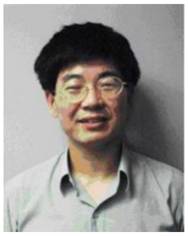

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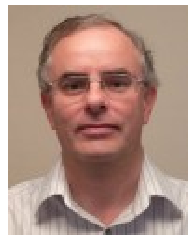

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