Experimental Studies of influence of DC and AC Electric Fields on Bridging in Contaminated Transformer Oil

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ABSTRACT

Analysis of real operating condition revealed that HVDC transformers experience combined effect of DC biased AC electric field. The dynamics of pressboard particle in contaminated transformer oil under the influence of DC, AC and DC biased AC electric field has been investigated in this paper. Different levels of particle concentrations are tested at different applied voltages. Optical images of the particles accumulation together with conduction current have been recorded during the experiments. A complete bridge between the electrodes of cellulose particles were observed for all the tests carried out under DC and DC biased AC electric field. Opposite to that, for AC experiments, pressboard particles accumulated on surfaces of both electrodes but did not create a full bridge between the electrodes. It is concluded that a combination of DC and AC voltages in a HVDC transformer could lead to a bridge formation within the equipment which could cause failure.

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. Failures 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].

Many high voltage applications including almost all high voltage power transformers use liquid dielectric oil. Transformer oil serves both as a heat transfer medium and also as an electrical insulation. However, it is very easy to be contaminated [3, 4], which deteriorates its electrical performance. Dielectric liquid inside a transformer usually contacts 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 presents within various area of a transformer. During operating condition the contaminant particles may get excessive charge or even tend to move towards high gradient of electric field regions due to dielectrophoretic (DEP) force. These contaminant particles could form a bridge over a period of time. The bridge may lead to partial discharges or total insulation failure if prevention measures are not taken. Such measures may include covering of conductors by paper or pressboard and introduction of convective flow of the oil. The former does not really helps as show in section 3.1 below, whereas the strong oil flow destroys the bridges.

Demand for HVDC transformer has increased as renewable energy sources like solar gaining popularity and more long distance DC transmission lines are to be built to meet energy requirements for 21st century [5, 6]. Analysis on operational HVDC transformer revealed that some parts of these HVDC converter transformers experience combined effect of AC and DC electric field [7]. Previously conduction current, partial discharges, resistivity [8 - 10] of bridging in transformer oil with DC and AC electric fields have been studied. Effects of particle size [11] and mathematical modelling [12] of bridging have been previously reported [13, 14]. The effect of combined DC and AC voltages has to be thoroughly investigated in order to understand the dynamics of contaminating particles. 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

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for each 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

The sample tank used for all the experiments was glass built and the total volume of this tank was 550 ml. Pair of spherical brass electrodes with 13 mm diameter have been used for the experiments. The electrodes were attached to either side of the test cell wall from which they extended towards the middle of the cell. The position of one electrode was fixed and another electrode could be moved using a screw drive. The distance between the electrodes was kept constant at 10 mm for all the experiments reported here.

2.2 SAMPLE PREPARATION

Cellulose fiber dust was produced by rubbing a piece of new pressboard used in high voltage transformer by metal files with different mesh sizes. Different sizes of sieves were used afterwards to separate the fibers. As a result, the particles were separated by the fiber width rather than length. The particles were categorized into four different sizes i.e. 250-500, 150-250, 63-150 and less than 63 µm. All the four sizes of particles were tested under DC electric field. All these 4 cases shown a consistent behaviour and only the results from 150-250 and 250-500 µm tests are discussed in this paper. 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 highest accuracy. For DC experiments only 0.001 to 0.004% contaminant were investigated whereas for AC all the above contamination levels used. In the case of DC biased AC, only 0.024% which was the highest contamination level was tested along with pure 3 kV DC electric field.

The contamination particles content was taken significantly higher in comparison with real operational conditions of HV transformers. It speeds up the process and allows to visualize the bridge formation without affecting the underlying physics.

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 fibers 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.

A water content of the oil can affect the dielectric constants and conductivities of both oil and the pressboard particles. To make sure that all experiments done at the same conditions, the water content of the oil is monitored by Karl Fischer titration method [15]. For all experiments presented in the paper the moisture content was between 20 and 24 ppm.

2.3 EXPERIMENTAL SETUP

The sample tank was positioned under a stereo microscope that had a digital camera mounted on the top to record the 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 were 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.

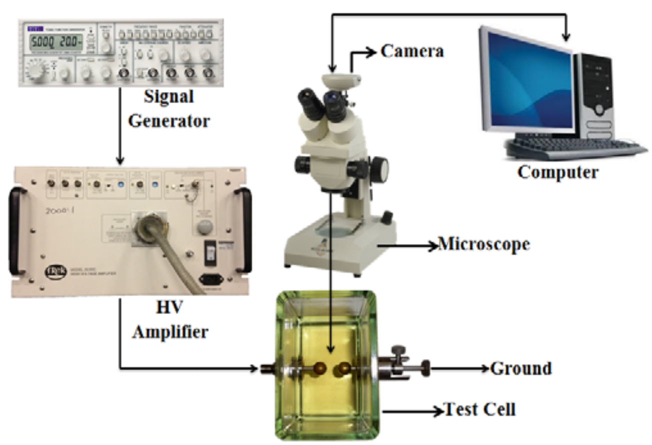

Figure 1. Experimental setup for DC biased AC test [14]

A block diagram of complete experimental setup for DC biased AC tests is shown in Figure 1. A detail description of DC experiments can be found in [11]. 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.

2.4 EXPERIMENTS UNDER DIFFERENT FIELDS

Three different voltage levels were investigated for each category of electric field, such as DC (2, 7.5 and 15 kV), AC (10, 15 and 20 kV peak-peak with constant supply frequency of 50 Hz) and DC biased AC (1, 3 and 6 kV DC offset with 10, 15 and 20 kV AC peak-peak with constant supply 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. The temperature of the aluminium box was monitored during DC test. The temperature was within 3 degrees difference for all the DC experiments. All the tests were conducted three times for each voltage level to observe the repeatability of the obtained results.

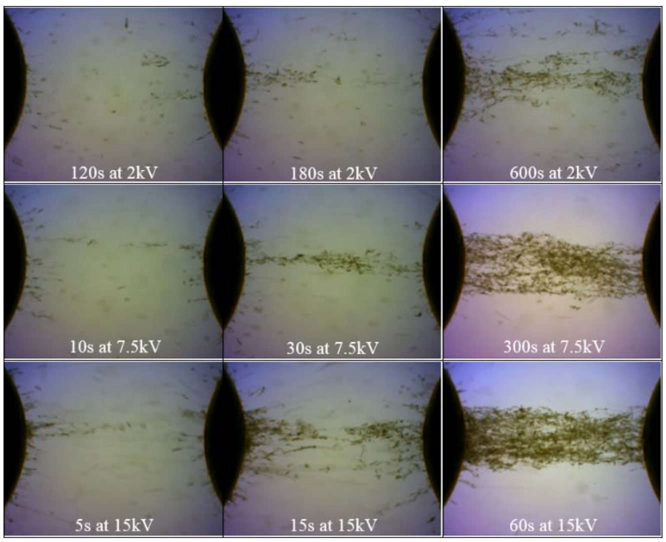

Figure 2. Optical microscopic images of bridging in contaminated transformer oil with 150-250 μm pressboard fiber, concentration level 0.003%.

3 RESULTS AND DISCUSSION

3.1 DC TEST

Figures 2 and 3 show the images obtained from two different fiber particle sizes at 2, 7.5 and 15 kV for a concentration level of 0.003%. It has been found that pressboard particles started moving between the electrodes after applying 2 kV. 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 fiber then align themselves parallel to electric field lines. Due to non-uniform electric field, the particles experience DEP force [16]. It can be seen at the initial stages of the experiment that fibers move towards the electrodes. Once the particles touch the electrode surface they acquire charges from the electrode. When the charge transferred to the fiber reaches a certain level and its repelling Coulomb force is greater than the attractive DEP force, the particle gets off the electrode surface and travel towards other 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.

The described behaviour is clearly seen on the current profiles, Figure 4. Initially the current is small, but since more and more fibers get an electric charge the current increases until it reaches a saturation which is different for different voltages and particles size. Previously this phenomenon has been investigated by several researchers [8, 11, 17-23] with conductive and dielectric particles. They have calculated the amount of charge acquired by both conductive and dielectric particles.

To understand the dynamics of the fibers we need to note that for long fibers of length *b* and sectional radius *a*:

Drag force [24] $F_{drag} \sim b(\mu v)$

Coulomb force [17] $F_C \sim qE \sim a^2V^2,\ q \sim a^2E$

DEP force [25] $F_{DEF} \sim a^2 b\nabla(E^2) \sim a^2 bV^2$

with E, V, μ, *v* being electric field, applied potential, oil viscosity and fiber velocity respectively. Many parameters in the above equations depend on moisture content. Since the moisture content remains the same during all experiments, the qualitative analysis can be done without taking into account these moisture effects.

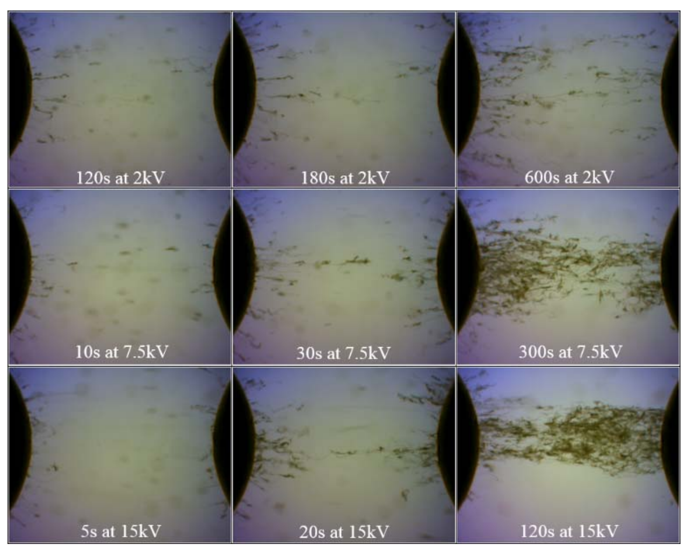

Figure 3. Optical microscopic images of bridging in contaminated transformer oil with 250-500 μm pressboard fiber, concentration level 0.003%.

The particles which did not acquire enough charge were stick with the electrodes surface due to strong DEP force. So the fibers move from electrode to electrode until they reach the point at the electrode surface where DEP force is high, which is close to the central line between the electrodes. The charged particles that are in contact with electrode attracted other particles with oppositely charges due to Coulomb force. The other attractive forces between particles within short distance are van der Waals force, dipole and quadruple interactions. The main component of the attractive force is the dipole iteration, when the voltage is switched off and the polarisation is removed, the particle fall down to the bottom of the tank under the gravity. Due to these inter-particle interaction forces, the pressboard particles started to form chain between two electrodes. These chains also align themselves parallel to electric field lines as can be seen in Figure 2, the particles upper or lower side of electrodes elongated following electric field line. Initially the electric field strength is maximum at the electrodes surfaces so is the DEP force. But since more and more particles stick to the electrodes surface, the maximum field and DEP force move to the ends of these particles chains closer and closer to the mid-point between the two electrodes. So the higher the voltage, the stronger DEP force pushes the fibers toward the electrodes at the start of the process and towards the central line at the bridge development stage. And as the result, for higher voltages the thinner, denser bridges are formed, see Figures 2, 3. Initially, longer fiber particles first stick on both electrodes where the DEP force is maximum. They start the bridging process by attracting other particles with smaller *b* on their surface forming a skeleton of the bridge which progresses towards the opposite electrode. Eventually the fibers chains from both electrodes contact in the middle.

After applying 2kV there was a thick bridge created after 600 s for 150-250 µm particles as shown in Figure 2. It took 180 s to make a complete thin bridge. There was a complete very tiny bridge formed after 180 s for the 250-500 µm particles as shown in Figure 3. A very shallow bridge was observed after 600 s. Couple of different branches were attached from one electrode to the other. The observed behaviour agrees with the proposed force balance. With increase of *b* (for the same *a*) the drag force increases whereas Coulomb force stays the same and it slows the particle motion towards the central region between the electrode. Note that the fibers have to be dragged towards the centre first and only after that the DEP force moves them to create the bridge.

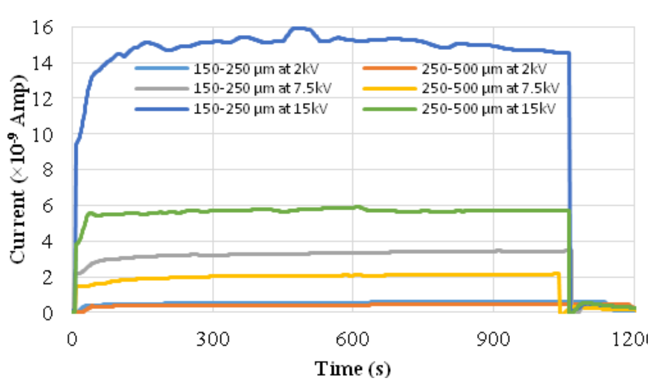

Figure 4. Conduction current at different voltages influenced by particle sizes with contamination level of 0.003% [11].

For 7.5 kV, a thin bridge formed after 10 s for 150-250 µm particles. The bridge was thickened until 300 s (Figure 2). There was no change of bridge formation observed after that. For 250-500 µm particles, a thin bridge formed at 30s and stared to grow until 300s as shown in Figure 3. The completed bridge for the bigger particles was shallow as compared with the smaller particles.

Similar observations were made after applying 15 kV. A thin complete bridge was made within 5 s, and thickened up to 60 s for 150-250 µm samples. On other hand, it took 20 s to form a complete bridge for bigger size particle. Within 120 s a thick bridge was created. The main point to be noted is that the thickness of the bridge and the bond between the particles of for smaller particles were far better than bigger size particle. It contradicts to the simplified force balance suggested in the paper. For larger fibers, further bridge compression is expected after 300 s with forming denser bridge. It does not happen partially probably higher friction forces between longer fibers as well a different quadruple interactions. But it is mainly due to the modification of electric field between the electrodes when the bridge is formed. The field gradient will be along the bridge in this case which stops the further bridge growth, see below.

The conduction current for the two particle sizes under the influence of three different voltage levels are shown in Figure 4. As soon as the voltage was applied, there was a high polarization current observed in most of the experiments. 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 through the pressboard particles under DC electric field.

The currents were almost steady after the bridge formed. The thickness of the bridge and the bond between the particles were the main determining factor for the conduction currents after this time. Although the bulk conductivity of the pressboard is several hundred times less than the transformer mineral oil, the high fiber surface conductivity allows the pressboard fibers to transfer a charge over the outer surface. The magnitude of the currents increased a great deal with the increment of contamination level. The currents for all the contamination levels increase with the contamination rise. The increment ratio of currents for smaller size and bigger size particles is different.

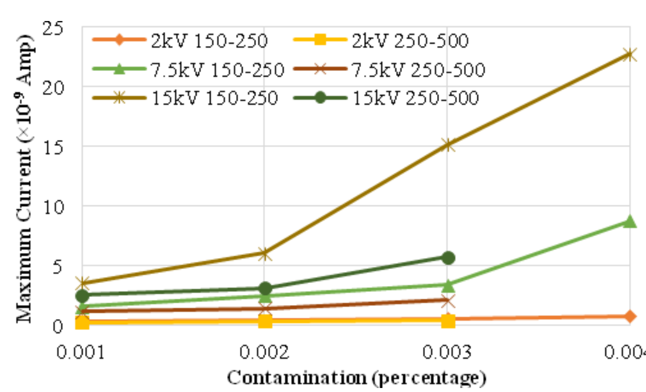

Figure 5. Maximum Conduction current in different concentration level [11]

The maximum conduction current (at the bridge stage) with respect to contamination levels for all the experiments are summarized in Figure 5. The highest point of steady conduction currents were taken for this graph. The two region of the process can be clearly identified for these plots. For low voltage of 2 kV, the current weakly depends on the particle size and contamination level. It is probably because the DEP is small to overcome friction force. Even the large number of particles is available to form the bridge, they cannot be compressed enough to form a long bridge. The current is approximately constant at 7.5 kV up to 0.003% contamination. After that it starts to rise. At 15kV the non-linear dependence becomes obvious. These results are in line with previous study by [8]. The most important observation out of this investigation is that the conduction current for 150-250 µm is always higher than 250-500 µm particles. To be more specific, the larger the size of the particles, the lower is the conduction current. Since it measured at steady state bridge, the contacts formed by smaller particles are always better. Please note that after the bridge is formed the mobility of the particles is irrelevant and the current is an indication of the bridge quality and the bridge its size.

The images for particle accumulation were analyzed using pixel counting technique. The first image of a particular experiment was taken as background and it was subtracted from all the later images. The result was obtained as a grey image with a specified tolerance level which was fixed for all the analysis to obtain consistent result. Then resultant image were converted into black and white. After that all the black pixels were counted. The quantity of pixel count does not correspond to the particles number but the increment of the pixels shows the particles accumulation between the electrodes.

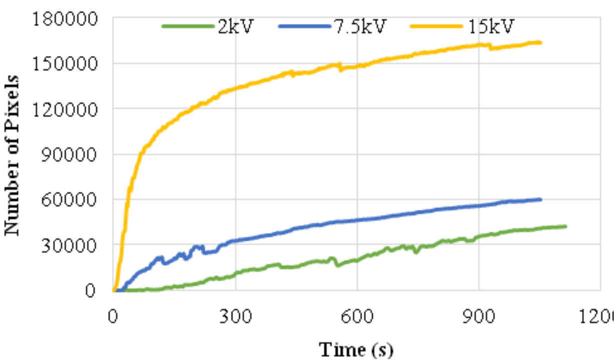

Figure 6. Increment of pixels in microscopic images under influence of DC electric field with 0.003% concentration.

The plots in Figure 6 shows the pixel counts for optical microscopic image taken during the test. The graph clearly indicates the increments of particles with time. But the current in Figure 4 reaches the saturation level much quicker. In other words, the additional particles which are brought in after the central bridge formation do not go towards the central region. It may be understood by considering the electric field changes as the bridge has been formed. The bridge itself is a reasonably good conductor and the field gradient will be along the bridge. So DEP force moves fibers towards the electrode in this situation, along the bridge, not making the bridge thicker.

It is important to understand the presence of paper and pressboard does not stop charge migration. It is obvious from Figure 7, where a Kraft paper sheet inserted between spherical electrodes does not prevent bridge formation even at low level of the contamination. This indicates electric charges migrate from one surface to another.

Figure 7. Optical microscopic images of bridging in contaminated transformer oil with 150-250 µm pressboard fiber and Kraft paper barrier, concentration level 0.001%.

It was shown in the experiments that all bridges formed can be destroyed by steering the oil. So the prevention measures should concentrate on finding a minimum convection speed which destroys the bridges.

3.2 AC TEST

Particle cloud formation at lower stress and dispersion at higher stress were observed and quantified by researchers [26, 27] previously. Figure 8 shows the images obtained at three different AC voltages for the highest concentration (0.024%) of fiber particles. It is clear that instead of forming a bride, the particles are attached to the surface of the electrodes more or less evenly. This behaviour is related to the alternation of the electric field. It is worth to note that The DEP force is 280 times higher than gravitational force estimated by [27] for a 50 micrometer diameter particle at 1 MV/m and gravity has a minor effect on the experiment. Once again, when the particles made a contact with the electrodes, they become charged. The particles which could not acquire enough charge to detach themselves from electrode surface (a balance between Coulomb and DEP force) stay on the electrode surface. Other particles may attach to these particles. These particle chains also elongate towards the other electrode parallel to electric field lines and form a beard as seen on Figure 8. If the charge is large enough, Coulomb force detaches the particles from the surface and they continue to move in the gap. But under AC, the particles travel towards opposite electrode only during a half cycle, after that the particles dragged back to the initial electrode. So, the particles make a short journey along the electric field line but the return journey does not is different mainly due to DEP force (which does not change the direction) and flow disturbance force caused by other particles.

Inter-particle interaction and DEP forces are the main reasons for particle segregation. The inter-particle force is not large, but it is sufficient to hold the particles attached to each other even when they form a conductive bridge. For example analysis of 50 micrometer diameter particle in 1.33 MV/m field showed [27, 28] that short range inter-particle interactions exceed the gravitational weight of the particle to the distances up to 6 particle radiuses. So while alternating field shaking the particles near the electrodes the DEP force, which does not dependent on the polarity of charge of the particle, drags the particles toward central between the electrodes where the electric field is the highest. Fluid movement due to the particles motion also helps in dragging neighbouring particles towards the electrodes. A single particle would drag all the particles at the distance of 10 times its radius along the direction of its movement [27]. A combination of the factors mentioned above and the electric field changes due to formation a conductive electrodes cover, results in evenly coverage of the electrodes without bridge formation. In the AC case the Coulomb force does not bring the particle to the central region between electrode and it prevents a bridge formation.

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 electric field. The pressboard particles started moving slowly when the 10 kV AC supply was applied. As time elapsed, particles were attached to both electrodes evenly, Figure 8. The particles accumulations increased to the electrodes surface with increment of both voltage and contamination levels. A complete bridge between the two electrodes was never created as for DC experiments because of the alternating polarity of the voltage. These results are in conflict with some previous reports [9] where the bridging was observed between spherical electrodes. Although the experiments used lower voltage, 6 kV, they were done in moistened transformer oil which may affect DEP force.

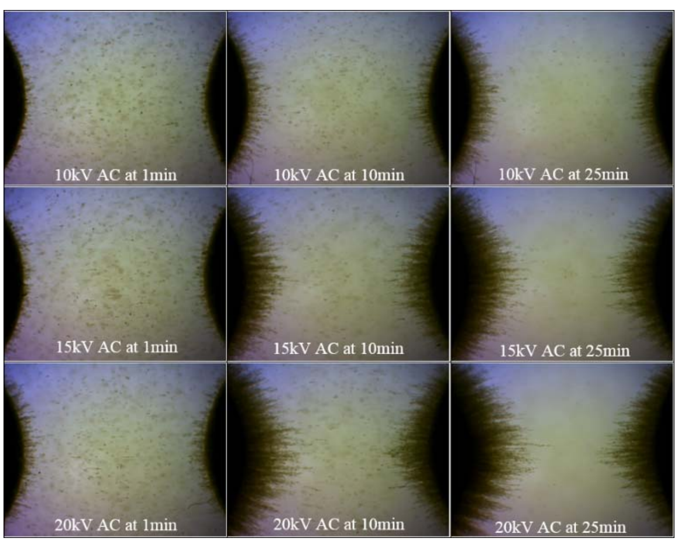

Figure 8. Optical microscopic image for bridging under influence of AC electric field with 0.024% concentration of 63-150 µm cellulose particles.

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 3 orders of magnitude higher than conduction current, Figure 4. Since complete bridge between the electrodes under AC electric field has never formed, the conduction current stays al low level. In fact the conduction current 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 fibers can be detached from the electrodes by Coulomb force.

Figure 9 shows the pixel counts graph under influence of different AC loads. The particle accumulation for 10 kV was slow because of weaker DEP force. Particles were attached to the electrodes almost at a steady pace during the whole experiment. The amount of particles accumulated for 15 kV was only little less than for the 20 kV test in spite of large increase in DEP force. It can not be explained based on the force balance and further experiments are needed to clarify the issue.

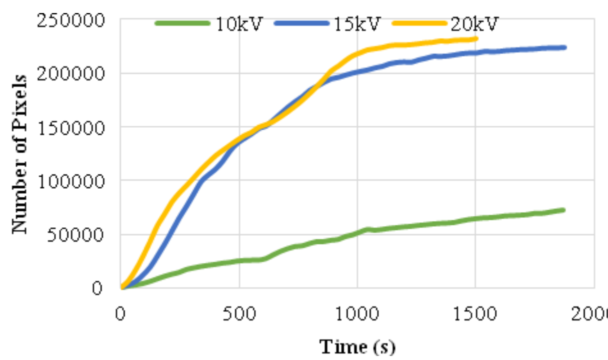

Figure 9. Increment of pixels in microscopic images under influence of AC electric field with 0.024% concentration [14].

For both 15 and 20 kV the particles accumulation was fast until 1000 s then it flattened. At this point, almost all fibers were consumed and the accumulation was stopped due to the lack of the fibers.

3.3 DC BIASED AC TEST

Three different DC offset levels investigated i.e. 1kV, 3kV and 6 kV. The AC voltage of 10, 15 and 20 kV 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.

The Figure 10 shows the typical observation. The first row of Figure 10 shows the result of 3 kV DC electric field. Then the followings rows are the result from 3 kV DC biased with AC voltages which enable us to visualize the difference bridging dynamics as a function of the AC load. There are many branches of the bridge which were formed within 30s 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 many branches of pressboard particle chain elongated from either side of the electrodes aligned themselves parallel to electric field lines. For 15 and 20 kV AC, 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.

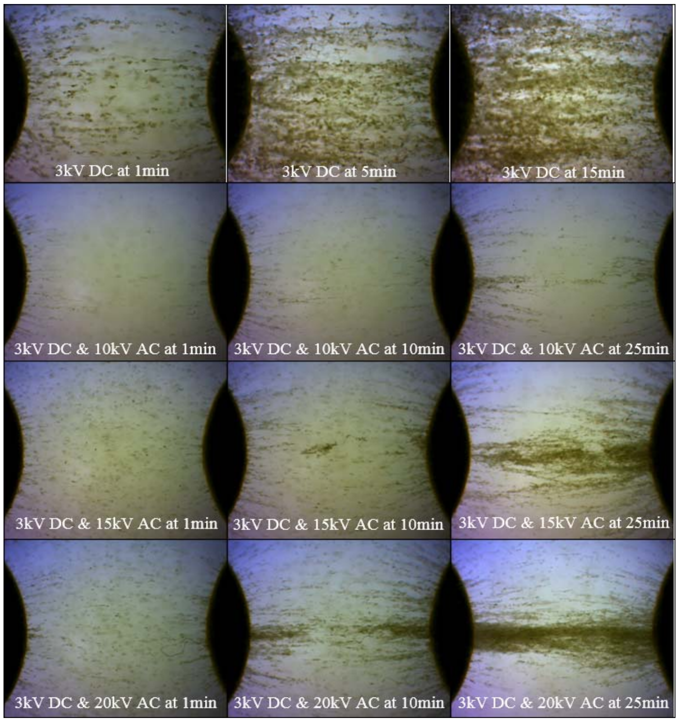

Figure 10. Optical microscopic image for bridging under influence of DC biased AC electric field with 0.024% concentration of cellulose particles.

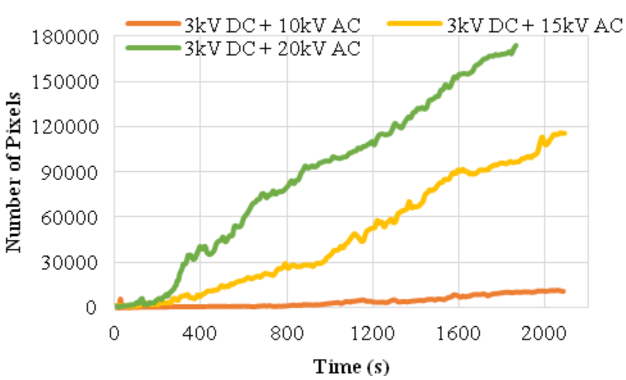

Figure 11. Increment of pixels in microscopic images under influence of DC biased AC electric field with 0.024% concentration.

To form the bridge the particles have to travel first to the electrodes, get a charge, be 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 affect DEP force. It means the addition of AC forces the fibers to stick to the electrodes and only a fraction of fibers can travel between electrodes. So it takes longer for the same number of "active", highly charged fibers to arrive to the electrodes. As the result the bridging dynamics is much slower. But the DEP force is much stronger with AC addition, it pushes fibers to the central line 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 fibers attaching to these chains.

Figure 11 shows the pixels counts under the influence of 3 kV DC biased with three different levels of AC electric field. The count for 10 kV AC did not increase much which is in line with the images of Figure 10. The growth is noticeable for 15 and 20kV cases. It is worth to notice that the particles accumulation was very slow until around 200 s for 15 and 20 kV. It is probably the time for sufficient number of "active" fibers to arrive to the electrodes surface. After that the growth takes place at constant rate up to the end of the experiments for both cases. The ratio of the slopes is approximately proportional to the applied voltage. It is an indication that the process is quite complex. It is controlled by a combination of the particles migration towards the electrodes, charging of the fibers together with DEP force both of which are proportional to V^2.

4 CONCLUSION

From the above results, several conclusions have been drawn.

Coulomb force is dominant factor for DC bridging. Although the contaminated particles brought to electrodes surfaces due to DEP force, after the contact they acquire charges from the electrodes and move to the other under influence of DC component of electric field. The particles which do not have enough repelling force (small charge) then stay attached to electrodes and they attract other oppositely charged particles. The attachment process is controlled by DEP force. This process leads to form complete bridge between the electrodes gap. As the voltage increased, the velocity of the particles and rate of bridge formation is intensified along with an associated conduction current. With an increase of DC voltage the bridges become wide but not denser. It is a result of the formation of the conductive path along the bridge and associated changes in the direction of DEP force.

The AC case shows absolutely different dynamics. The time averaged DEP force brings the particles to the electrodes surfaces. The particles acquire a charge during one half cycle and change of polarity prevent them to travel to the other electrode. Instead they are shaken in the vicinity of one electrode and form a beard. The particles don't create complete bridge opposite to the DC case. They cover only the electrode surfaces, the points where the DEP force is maximum. The overall rate of particles accumulation for AC case was slower than the DC one at the same voltage levels.

The DEP force and Coulomb force both act on the particles when the DC and AC voltages are combined. DEP force brings the particles to the electrodes surfaces, the particles get a charge, they start to move towards opposite electrode if the charge is large enough to overcome DEP force. As they move, strong DEP force brings them to the central line between the electrodes. The particles collide with each other and discharges between the particles take place. It reduces the particles mobility and creates bridge in the middle of the electrodes. Although the bridging dynamics is slower in comparison with pure DC case, the formed bridges are denser.

The risk of creating bridge in a HVDC converter transformer is very likely where there is DC with AC voltage is present. Paper or pressboard insulated metal parts do not stop bridging; oil convection is needed to prevent bridging.

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