# Effect of Different Shapes of 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 were always formed bridges between electrodes under DC electric field. AC field does not induce any bridging. Combination of AC and DC enhances the bridging dynamics. The bridges were thicker or more particles attracted with more uniform electric field (spherical electrode) than diverse electric field (needle-plane).**

***Keywords—HVDC transformer, failure, contamination, Dielectrophoresis, drag force, bridging, transformer oil.***

## I. Introduction

Power transformers are one of the key components in high voltage transmission and distribution systems and their consistent operation is of utmost importance to energy utilities and users. A significant transformer failures are caused by insulation oil contamination. Understanding the failure mechanisms will allow us to take preventive measures [1].

During the operation oil is in contact with metal, iron core and pressboard insulation. Contaminants such as metal filings or cellulosic residue can be formed in the oil, especially for transformers with aged paper insulation. Non-uniform fields are present within the transformer. These contaminants tend to move towards high field regions due to dielectrophoresis (DEP) forces [2]. Once in the high field regions, these particles may acquire a charge when in contact with different parts of the transformer and contribute to a leakage current [3]. They also could form a bridge over a period of time. The bridge may potentially act as a conducting path between two different potentials within the transformer structure, leading to partial discharges or insulation failure. We have reported previously the bridging with bare spherical electrode under different combinations AC and DC electric fields as well as mathematical model of the bridging [2-6]. This paper focuses on the effects of strong non-uniformity of an electric field in the vicinity of sharp edges and how it affects the bridging.

The experiments have been carried out to investigate the particles' accumulation between two different shapes of electrodes under different conditions: AC, DC and AC biased with DC voltages. The paper presents the details of the experimental setup and explains the observed results. Three different levels of AC and DC voltages were investigated for these experiments for needle-plane and spherical sets of electrodes. Different levels of contaminations were also examined. Optical images of bridge formation process were taken and conduction current was also recorded simultaneously during all the tests.

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## II. Experiments

### *A. Test Cell*

The sample tank used for all the experiments was glass built with a volume of 550 ml. Two different electrode systems were used for the experiments, such as sphere-sphere electrode and needle-plane electrode systems. A pair of brass spherical electrodes with a diameter of 13 mm have used for the sphere-sphere experiments. The needle electrode was made of tungsten and had a tip diameter of 100 µm. The plane electrode was made from brass with a diameter of 50 mm and thickness of 5 mm. The electrodes were attached to either side of glass tank from which they extended towards the middle of the cell. The gap between the electrodes for both electrode systems was kept constant at 10 mm for all the experiments.

### *B. Sample Preparations*

Pressboard fibers were produced by rubbing an unused pressboard typically used in high voltage transformer by different sizes of metal hand files. Different sizes of sieves were used to separate the fibers by width rather than length 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. Only the results from 150-250 µm 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. 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. 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.

A new test was always started with adding 300 ml of transformer mineral oil into the test cell which submerged the electrodes under oil. The lowest contamination level of fibers was then added. The sample was stirred prior to every test on a magnetic stirrer for 2 minutes to disperse the particles.

### C. Experimental Setup

The test cell was positioned under a microscope that had a digital camera mounted on the top to record optical images. Only for DC test, the microscope along with the test cell was placed inside an aluminium box which acts as a Faraday cage to reduce a possible noise. Either one of the spherical or needle electrode was connected to the high voltage source. The other spherical and plane electrode was connected to the ground via a Keithley picoammeter 6485 (DC) and Keithley multimeter 2001 (AC) to measure the current. A desktop computer was used to control the digital camera, to collect data from the camera, and also for the conduction current measurement.

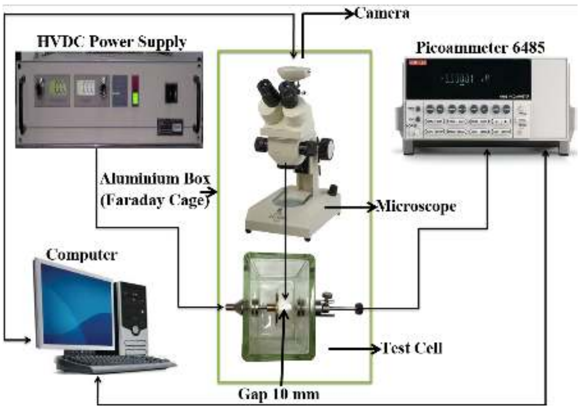


Fig. 1. Complete block diagram of experimental setup under influence of DC electric field with needle plane electrodes [2].

A block diagram of experimental setup for DC tests with needle-plane electrodes is shown in Fig. 1. A detail description of DC tests can be found in [2]. DC biased AC test consisted of a signal generator, high voltage amplifier, sample tank/test cell, microscope, digital camera and computer. The signal generator produced AC voltage of 50 Hz with a DC offset. This signal was amplified 2000 times with the high voltage amplifier from TREK, Inc. The amplified signal was connected to one electrode and the other connected to the ground.

Three different voltage levels were investigated for each category of voltages, such as DC (2kV, 7.5kV and 15kV), AC (10kV, 15kV and 20kV) and DC biased AC (1kV, 3kV and 6kV DC offset with 10kV, 15kV and 20kV AC). Each experiment was carried out until a complete bridge was created between the electrodes or maximum of 25 minutes when there was no bridge. Images were taken in a regular interval during the entire test to record the bridging process along with some videos. All tests were performed at ambient room temperature.

## III. Results and Discussion

### A. DC Test

*Spherical electrodes:* The images obtained from the experiments using two different electrode systems are shown in Fig. 2 and 3. The fibres started moving between the electrodes upon the voltage application. When the power is applied to the system, under DC electric field the particles start to become polarized. The fibers then align themselves parallel to electric field lines. The particles experience DEP force and the fibers move towards the electrodes. Once the particles touch the electrode surface they acquire charges from the electrode. When the charge transferred to a fiber reaches a certain level and the repelling Coulomb force acting on the fiber 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. 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.

After applying 2kV, a complete thin bridge was created within 180s. There was a few shallow bridge created after 600s for spherical electrodes as shown in Fig. 2. A few different branches were attached from one electrode to the other. For 7.5kV, a thin bridge formed after 10s. The bridge was continued to grow until 300s (Fig. 2). After that, no changes of bridge formation were observed. After applying 15kV, a thin complete bridge was made within 5s, and the bridge was thickened up to 60s. A detailed explanation of the mechanism of bridging under DC electric field can be found in our previous report [3].

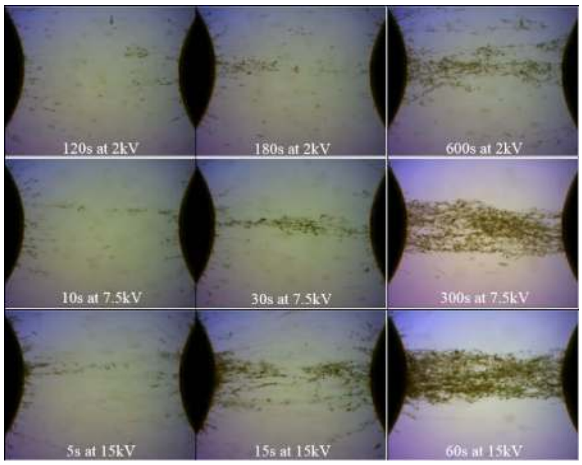


Fig. 2. Optical microscopic images of bridging in contaminated transformer oil with 150-250 μm pressboard fiber using sphere-sphere electrodes, concentration level 0.003%.

*Needle-plane system:* DEP force draw the fibres close towards high electric field gradient region at the needle tip.

Then the particles were charged from the positive needle and discharging on the other side. The fiber 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 fiber particles. The fibers attached to the needle and align themselves parallel to the electric field lines. Then the small particles attached to the long fibers. This process continues until they form a full bridge between the electrodes. There were some pressboard particles attached to the needle electrode after 120s of the 1 kV power supply turned on but there was no complete bridge formed even after 900s (Fig. 3).

For 3 kV, the particles were accumulated towards the electrodes and started to attach themselves within 30 seconds. There were a few braches of the bridge formed within 120 s and it continued until 600 s.

The bridging process accelerated for 6kV, bridge formed within 10s. Couple of branches of the bridge formed as soon as 60s and continued until 300s. The bridge was more compact than 3kV.

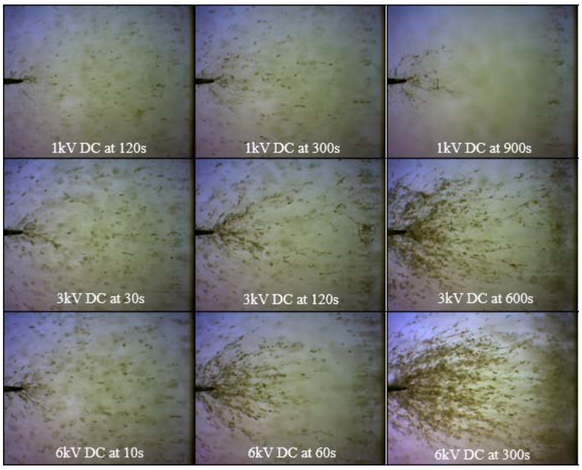


Fig. 3. Optical microscopic images of bridging in contaminated transformer oil with 150-250 µm pressboard fiber using needle-plane electrodes, concentration level 0.024%.

## B. AC Test

*Spherical electrodes:* The pressboard fibres started moving slowly when the 10 kV AC turned on. Particles were attached to both electrodes evenly, as shown in Fig. 4. The particles accumulation amplifies with increment voltage and contamination levels. A complete bridge between the two electrodes was never created for any AC voltages. The particles cannot leave the surface of the electrodes because of alternating Coulomb force as well as DEP force always pushes particles towards electrodes.

The current stays at constant level as a complete bridge between the electrodes under AC electric field has never formed. 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. But they are attracted back to the electrodes at the next half-cycle.

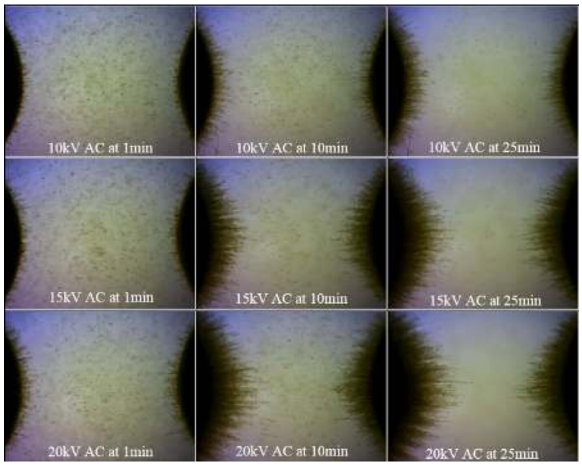


Fig. 4. Optical microscopic image for bridging under influence of AC electric field with 0.024% concentration of 63-150 µm particles.

*Needle-plane system:* The AC voltage was slowly increased to desired level of 5 kV. The particles were started to move slowly towards the electrodes due to 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 and very few on plane electrode until 25 min.

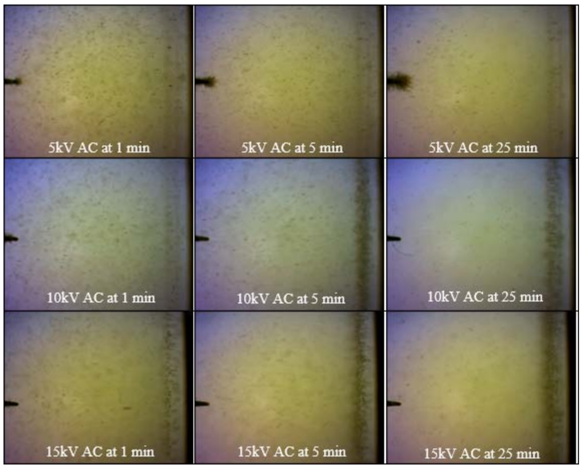


Fig. 5. Optical microscopic image for bridging under influence of AC electric field with 0.024% concentration of 63-150 µm particles.

The particles were started to move from the needle towards the plane electrode due to electro-convective flow at 10kV or above. The high electric field creates two vortexes waves propagating from the needle to the plane [7]. 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 5kV load. There were charge injected to the oil at the needle and the oil moves towards the plane dragging the fibre particle. The charge injection is only noticeable at 10kV. The particles accumulated on the surface of plane electrode experience a combination of DEP force and the drag force due the oil flow. Similar phenomenon was observed for 15kV.

## C. DC biased AC Test

*Spherical electrodes:* All of three levels of DC voltage showed that as the AC voltage increased, the thickness of the bridge also increases for spherical electrodes. Fig. 6 shows a comparison of 3 kV DC electric field combined with different AC loads. It visualizes the difference in bridging dynamics as a function of the AC load. There are many branches of the bridge formed within 30s after the 3kV DC supply switched on. The thick but shallow bridge was formed over a period of 15 min. When the 3kV DC was combined with 10kV AC, a very thin bridge was created after 20 minutes. A complete bridge formed between the electrodes after 10 minutes and 5 minutes respectively for 15kV and 20kV AC. So the bridging process is much slower in comparison to pure DC electric.

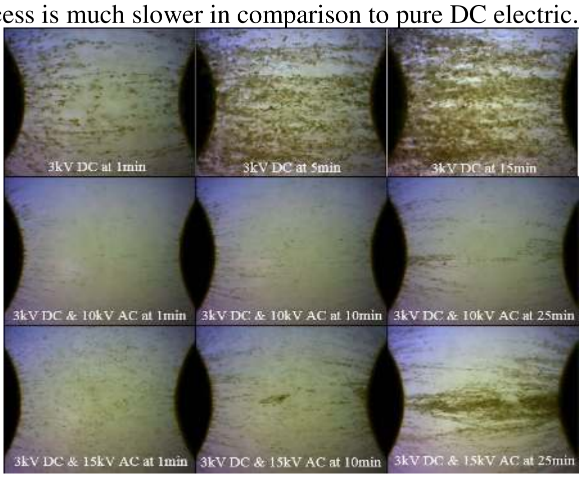


Fig. 6. Optical microscopic image of bridging for kraft paper barrier test under influence of DC electric field with 0.003% concentration of 150-250 μm cellulose particles.

*Needle-plane system:* AC voltages of 5 kV, 7 kV and 10 kV were used with a DC offset of 3 kV for needle-plane system. 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.

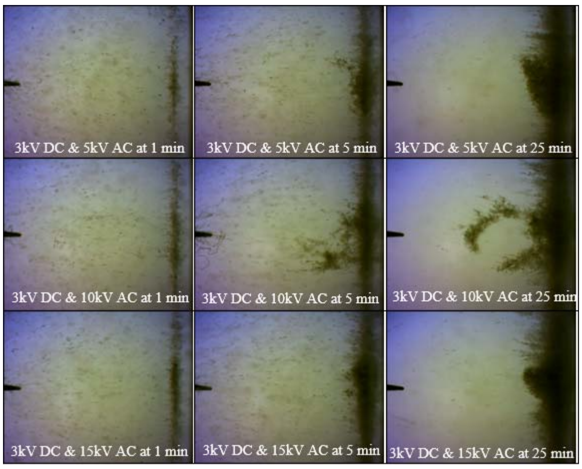


Fig. 7. Optical microscopic image for bridging under influence of DC biased AC electric field with 0.024% concentration of cellulose particles.

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. Strong electro convective force does not allow particles to stay at the needle tip and pushed towards plane electrode. More particles were attached to the plane electrode than in pure AC test. So DC voltage helps to accumulate more particles to the plane electrode.

# IV. CONCLUSION

The bridge is thick and strongly bonded for spherical electrodes under DC voltage. A shallow bridge is formed for needle-plane electrodes system under similar DC voltage. In the first case DEP force is high enough over a large volume of oil. But for the needle-plane system the force is very strong near the needle tip, but become very weak near plane electrode and in the majority of the oil volume. So the particles (after charge injection) travel along the field lines without being concentrated near the central line connecting two electrodes. For AC load, a very strong DEP force brings more the particles to the electrode surfaces and not allows fibers to move away. 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 for needle-plane electrode system. When the voltage increases, the needle electrode induced an electro convective force and it moves all particles to the plane electrode and fixes them on it. DC biased AC voltage produces large charge injection into the oil. As a result of string electro convective flow, 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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