PARTIAL DISCHARGE CHARACTERISTICS DUE TO AIR AND WATER VAPOR BUBBLES IN OIL

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Abstract: Air and water vapor bubbles may occur in power transformers as a result of high local electrical or thermal stress. When the bubbles are exposed to a high electric field they will cause partial discharges. Some of these partial discharges may be harmful for transformer insulation and some may not. This paper discusses the signatures due to partial discharges from free air bubbles or water vapour bubbles in oil, bubble in contact with pressboard, a cavity embedded in pressboard and from a metal object at floating potential. Experimental setups were developed to evaluate the partial discharge patterns and the change in inception voltage at different temperatures. The influence of bubble size on partial discharge pattern is discussed. The difference in behavior between partial discharges in free oil and partial discharge in cavities and from metal objects at floating potential is discussed.

1 INTRODUCTION

The power transformer is a key component in the power system. A transformer failure must be avoided because of considerable cost either due to outage or replacement of the transformer. A significant number of failures in power transformers are due to insulation malfunction. Partial discharge activity is usually an early signature of a failure that may lead to insulation degradation with a short circuit as the final consequence. Most of the transformers that are used in the network are oil-filled transformers and this motivates the need to investigate the characteristics of partial discharges in oil under different conditions such as stress distribution, oil temperature, oil humidity and other contaminations. There are different sources of partial discharge in a transformer such as void in pressboard, moving bubble, surface discharge on winding, corona from metallic protrusions in oil etc. In a previous paper [1], PD patterns relevant to corona in oil and corona inception voltage as a function of geometry, temperature and humidity, was reported. Shiota et al, in [2] and Chen et al, in [3] have investigated partial discharge activity due to bubbles in oil. Borsi et al, in [4-5] have investigated the effect of temperature and humidity on corona in oil. In this paper, efforts are made to characterize PD phenomena occurring in air and water vapour bubbles when exposed to high AC electric field with the aim to achieve signatures of a partial discharge due to moving gas bubbles in oil or bubbles trapped adjacent to the pressboard. The effect of the size of bubble on PD inception voltage is investigated. PD pattern due to metal object at floating potential is obtained and the effect of temperature on their inception voltage is investigated.

2 EXPERIMENTAL SETUP

A schematic of the measurement system and experimental model for a moving bubble and for bubble adjacent to pressboard are shown in figures 1 and 2. Photos from the test setup are shown in figure 3.

The setup consists of two brass-electrodes in between which there is a sandwich structure of pressboard and oil. The diameter of brass-electrodes is 90 mm. Next to each electrode there is one sheet of 5 mm thick pressboard and in between there is a variable oil gap which here has been set to 10 mm. The model is immersed into Nytro 10XN transformer-oil. For the moving bubble experiment air bubbles are passed through the oil gap between two electrodes by using an air pump and a very narrow tube. For the experiment with the bubble adjacent to pressboard, a micro syringe is used to inject a bubble below the top pressboard or metal electrode. A bubble injected below the bare metal electrode will not stay below the flat metal electrode, but escape the gap. If one manages to get the bubble to stay it will immediately after applying the voltage move out from the oil gap. To solve this we made a top electrode that has a very little cone type curve on it to let the bubble stay in the center of the electrode. To do the experiment for bubble adjacent to pressboard when the bubble size is smaller than 10 micro litres we use an oil gap of only 3.5 mm to reach the PD inception electric field.

After placing the bubble by using the micro syringe, a 50 Hz AC voltage was applied to the test setup and increased in steps of 2 kV with 1 minute duration until partial discharges started. By repeating this process for several times and by taking the average value for inception voltage we obtained the inception voltage of partial discharge for bubble in oil. An ICM system was used to record PD patterns and a Tektronix TDS 3052 oscilloscope was used to capture single PD pulses.
3 RESULT

3.1 Moving Air Bubbles and cavity embedded in pressboard

Partial discharges that occur in a free bubble are supposed to be much less harmful than those partial discharges that are due to a void inside a solid insulation or between the layers of paper. The PD pattern due to moving bubble and due to a void between the pressboard layers was measured. By using a pump with a valve, different size of bubbles could be passed through the oil gap between the two electrodes that are covered with pressboard. These two layers of pressboard are mainly used to avoid complete discharge between electrodes. The bubble flow rate for small bubbles was 25 bubbles per second. Figure 4 shows the PD pattern for moving bubble under a voltage equal to 1.25 times the inception voltage.

Figure 3. Photo from test setup, a) moving bubble, b) bubble adjacent to pressboard

Table 1 shows the relation between the size of bubbles and the PD inception voltage.
Happen between zero-crossing and the peak of voltage. After a discharge in a moving bubble the bubble disintegrates into smaller bubbles and partial discharge inception voltage for those smaller bubbles are higher and also bubbles are between electrodes only for fraction of a second so the space charge due to previous discharge has a much less pronounced effect on PD pattern.

When the bubbles pass through the oil gap they stretch and relax along the electric field with a frequency of twice the frequency of the applied voltage i.e. 100 Hz in this experiment. Each PD pulse is corresponding to the disintegration of the bubble. Figure 7 shows how bubbles stretch along the electrical field and how the bubble disintegrates after the PD signal.

3.2 Moving Water Vapour Bubbles

To increase the temperature of oil from 0 to 100 °C the circulating water heater was used. By using this heater one can reach to fix temperature below 100 °C that was used to see the effect of temperature on partial discharge due to a metal object at floating potential and bubble adjacent to pressboard. To go above the 100 °C one can use a heating plate that was placed under the oil’s tank.

To obtain water vapour, at first oil temperature was increased to 108 °C, after that number of very small water droplet was injected on the bottom of the oil tank, exactly below the gap between the parallel electrodes. Immediately water started to evaporate and moving water vapour bubbles raised between the parallel electrodes. In this case the test setup consisted of two brass electrodes with the oil gap equal to 13 mm between them. The PD pattern for moving water vapour is shown in figure 8. One can see that moving water vapour bubbles behaves similar to moving air bubbles. With a PD pattern that is symmetric and they mostly happen around the peak of sinusoidal voltage. In this experiment the size of the water vapour bubbles were not equal. Most of the time small bubbles were generated and passed through the oil gap in spite of that sometime medium and large bubble were also generated and passed.
through the oil gap. Because of this one can see there is a little concentration of PD between the 30 to 60 phase degrees on the PD pattern.

![Figure 8](image)

**Figure 8:** PD pattern for moving water vapour at 1.2×Inception

### 3.3 Bubble Adjacent to Pressboard

Different sizes of bubbles are placed under the top electrode and after increasing the voltage in steps of 2 kV the inception voltage for each case was recorded. The experiment was repeated several times to have an accurate estimation of the inception voltage. It was observed for bubbles larger than 1 micro litre that after the first discharge the bubble was disintegrated into two or more smaller bubbles and after that partial discharge activity extinguish. Figure 6 a,b show two recorded PD pulses for 5 and 100 micro litre bubbles. They indicate that the PD pulse occurs near to the peak of the sinusoidal voltage. Measurement is done for different size of bubbles and by using equation 1, one can say that for different bubble size the inception electric field is:

$$E_{oil} = \frac{V_{oil}}{d_{oil}} = \frac{V_{tor} \varepsilon_{oil}}{d_{oil}} = \frac{V_{oil} \varepsilon_{oil}}{d_{oil} + \frac{2 \varepsilon_{oil}}{\varepsilon_{oil} + \varepsilon_{PB}}}$$  \hspace{1cm} (1)

- $V_{oil}$: Applied voltage across the electrodes at the inception voltage
- $E_{oil}$: Voltage across the oil gap
- $\varepsilon_{PB}$, $\varepsilon_{oil}$: Permittivity of pressboard (4.2) and oil (2.2)
- $d_{PB}$, $d_{oil}$: Pressboard and oil gap thickness (5 mm and 10 mm respectively)

The electric field inside different size of bubbles was calculated by using COMSOL [6] and by using Paschen’s curve the breakdown field in those bubbles was estimated. Figure 10 shows the COMSOL simulation.

![Figure 9](image)

**Figure 9.** PD signal due to a bubble adjacent to pressboard, a) for 5 micro liter bubble, b) for 100 micro liter bubble

Figure 11 shows the relation between PD inception electric field and bubble volume from COMSOL calculation and from measurement. It appears that inception voltage is different between calculation and measurement. One reason is that in reality the bubble that is adjacent to the pressboard is not spherical at the moment of partial discharge. Figure 12 shows how the bubble shape change after applying voltage.

![Figure 10](image)

**Figure 10.** Electric field distribution within and around a bubble adjacent to a pressboard surface

![Figure 11](image)

**Figure 11.** Relation between bubble volume and inception electric filed
For very small bubbles because of surface tension, their shape will be very close to spherical when it leans to pressboard. At increasing voltage the small bubble starts to elongate in the direction of the electrical field. As a result the field enhancement decrease and voltage that is needed to cause breakdown in the bubble increase. Since we consider a spherical bubble in COMSOL, as a result the inception voltage from COMSOL is lower than the experimental result. For medium bubble after applying voltage the bubble starts to elongate in the electrical field and it become very close to a spherical shape so the result from experimental and COMSOL are very close. The large bubble resembles the shape of an ellipsoid (or oblate spheroid) before the application of voltage and by applying voltage it elongates in the direction of the electric field. However, PD inception is reached before the shape becomes spherical i.e. the field enhancement is higher than for the spherical case computed by COMSOL and the apparent inception field is lower than estimated.

As one can see from figure 8 even when we use only metal brass electrode on top (without pressboard) again the inception electrical field is different with the time that we use pressboard on top electrode. The reason could be because of the very small cone shape on top electrode or because of bubble shape that is different when it is next to brass electrode compared to pressboard and as a result the inception electric field is different in the two cases.

It was observed that after disintegration of the 1 micro litre bubble into very small bubbles then there was a continuous partial discharge activity around the peak of the voltage. If the voltage then was increased further it was observed that some of those very small bubbles moved downwards to the lower pressboard, which is an indication of existing surface charges on the pressboard surfaces and that a net charge can be carried on the surface of small bubbles. After reduction of voltage they moved upward.

3.4 Metal Object at Floating Potential

A metal object at floating potential may exist inside a power transformer if it has lost its contact to the winding or to earth. To simulate a floating metal, a piece of copper wire was hanged inside the chamber of oil and placed 1 mm far away from the high voltage electrode. Figure 13 shows the test setup for testing a lose connection. Figure 14 shows the PD patterns for this floating wire at an oil temperature of 40 °C and 98 °C. It appears that PD pattern for a metal object at floating potential happens mostly between phases 10-120 degree and 190-300 degree in 50 Hz cycle. As one can see from the figure 14 the repetition rate of PD will decrease when temperature increase. This phenomenon is similar to corona in oil [1].

![Figure 13: Test setup for a loose connection](image)

![Figure 14: PD pattern due to floating wire close to the high voltage electrode at 1.25×V inception, a) at 40 °C, b) at 98 °C](image)
3.5 Temperature Effect

The temperature effect on inception voltage of bubble adjacent to pressboard and of metal object at floating potential was investigated. Figure 15 shows the effect of temperature on partial discharge inception voltage for an air bubble adjacent to pressboard and figure 16 shows the effect of temperature on partial discharge inception voltage for floating copper wire near to the high voltage electrode.

![Figure 15: temperature dependence of partial discharge inception voltage for a bubble adjacent to the pressboard](image1)

As one can see in figure 14 when temperature increases the partial discharge inception voltage for bubble adjacent to pressboard will decrease. The explanation may be that when temperature increase the viscosity of oil will decrease. A decrease of oil-viscosity will result in a reduction of surface tension between oil and air bubble and while bubble leans to top electrode it can stretch horizontally more than the case that temperature is lower. It is clear that a flat bubble cause a higher field enhancement than a spherical bubble so the partial discharge inception voltage decrease with the increase of temperature.

For a metal object at floating potential the partial discharge inception voltage will increase this behaviour is similar to corona [1] as temperature increase.

4 CONCLUSION

In this paper, partial discharge patterns due to air and water vapour bubbles in oil, air filled cavity and metal object at floating potential under AC electric field was investigated. PD patterns show that partial discharge due to moving bubbles happens symmetrically around the peaks of the sinusoidal voltage. This characteristic allows distinguishing this kind of discharge from the discharge due to a void that is embedded in a solid insulation or due to a bubble between the layers of paper. Investigation for a bubble staying adjacent to the pressboard has shown that after the first PD the bubble disintegrates into small bubbles and because the inception voltage for smaller bubble is higher than for larger bubbles the PD activity will stop. PD pattern due to a metal object at floating potential shows that PD occurs symmetric in both cycles. Tests shown that temperature has effect on inception voltage of an air bubble in oil and by increasing the temperature the PD inception voltage decrease but for floating metal an increase in temperature will result in significantly higher PD inception voltage.

5 REFERENCES


