Influence of sinusoidal and square voltages on partial discharge inception in geometries with point-like termination

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Abstract: High-voltage equipment involves both electrical and electronic components. In electrical power network, which consists of rotating machine, power transformers and transmission lines, field enhancement at critical regions can lead to local breakdown (partial discharges (PD)). The continuous occurrence of PDs can lead to complete breakdown. While in large power equipment sharp edges can be avoided, this is not the case in power converter due to the miniature nature of the semiconductor device. Sharp edges can also be present in any power equipment in the shape of conducting particles, either stuck at a barrier or freely moving in the bulk oil. This creates high-field regions, prone to PD activities. Different power equipment operates at different voltages such as AC, DC, square voltage, pulse voltage, fast-rise transient voltage etc. This study presents the influence of sinusoidal voltage, slow- and fast-rise square voltage on PDs in two different geometries using optical PD measurement technique. Fast-rise square voltage has the lowest PD inception voltage while the sinusoidal voltage has the highest. This is may be due to the influence of homo- and hetero-charges. Fast-rise square voltage displayed higher PD magnitude at inception which may be connected to the rise time of the voltage.

1 Introduction

In recent years, quite a number of works has been done to obtain detailed information about partial discharges (PDs) and electrical breakdown in dielectric solids and liquids in power equipment [1–6]. There are various geometries in power equipment that could influence field distribution but the most favourable electrode configuration for high voltage experiment in laboratory has been the point-plane geometry. This geometry is often preferred because the point yields a high-electric field even at moderate voltages [2]. It is also easy to view the effect of polarity reversal on discharges with point electrode. In insulating liquid for example, it is commonly known that application of alternating electrical field generates free space charges in the liquid at the tip of the point electrode. This is due to electric field dependent ionic dissociation, electric field dependent molecular ionisation and electrode mechanisms such as field emission and tunnelling. When charge is injected (homo-charge) in the bulk, they are transported away from the high-field region. This will reduce the field edge during the first half cycle. In the second half of the cycle where polarity reversal occurs, the homo-charges become hetero-charges and enhance the field. The newly injected homo-charges remain within the high field region counteracting the influence of the hetero-charges [2]. The forces on the homo-charges dominate as the field within the vicinity of the charge is higher than the field around the hetero-charges. The newly created homo-charges closer to the triple point are transported away. The total electric field is changed by these space charges, influencing the probability of PD inception. This process has influence on the time for PD inception. The electrode geometry and configuration as well as the voltage type has influence on this process, thereby affecting the PD inception voltage (PDIV) and the PD magnitude. The transport of these injected charges may also be dependent on the presence of solid dielectrics adjacent to the point electrode [7]. Occurrence of PD leads to voltage drop across the discharge channel. The field at the point electrode might not be large enough to sustain ionisation of the liquid molecules at relatively low voltage and the PD will disappear. However above a critical voltage, further ionisation of the liquid molecules at the high field region is sustained and propagation of streamers occur [8]. Surface discharges may develop which creeps along the surface of the adjacent dielectrics immersed in liquid [9]. This may leave traces of conducting particles behind, leading to further degradation of the dielectric strength of the insulation system.

When a PD occurs, locally stored energy is released and transformed to other forms of energy as shown in Fig. 1. Chemical change such as breaking of bonds in molecules is produced in the insulation during the discharge. The discharges may also lead to thermal effects due local heating of the surroundings. Local excitation of molecules leads to emission of light after relaxation. Discharges may emit light which can be observed visually in the dark. The discharge occurs like a small ‘explosion’ and emits mechanical waves. This explosive effect may be utilised for acoustic detection of the discharges. There is the possibility of electromagnetic waves emission during PD process. PD can be detected using this effect by means of aerials that either detect the magnetic or the electric field. Moreover, a transient voltage is observed at the connected terminals. This gives the current impulses that integrated up to give a charge \( Q_{apparent} = \int \Delta i dt = \Delta U \cdot C_0 \). This is what is normally measured when one measures discharges [10].

Real oil-filled power equipment has composite insulation system that consists of solid and liquid insulation of various shapes and configuration. The point-plane geometry in power equipment may be in the form of unavoidable sharp edges or could be present...
in the shape of conducting particles, either stuck at a barrier or freely moving in the bulk oil [11]. The conducting particle does not have to be in direct contact with an electrode to generate PDs and breakdown [12]. However, breakdown may also occur in power equipment as a result of local field enhancement due to unavoidable wedges, and the presence of moisture.

There are challenges faced in an attempt to use the conventional electrical PD technique in the measurement of PDs under different voltage shape. Measurement of electrical PD under sinusoidal voltage has no challenges but PD measurement under ac square wave voltage is accompanied with load current which does not change sign abruptly when there is voltage polarity reversal. The measurement system records this load current (noise) as discharge. This noise occurred as soon as the voltage source is turned on making it difficult to know the inception of PDs from the test object. This noise with high amplitude obscured the actual PDs from the material or component under test. It becomes difficult to differentiate between the actual PD and the registered PD due to the noise, thereby making electrical PDs recorded under square voltages unreliable. Efforts are made towards a reliable technique for detection of PDs under square voltages. Ultra-high frequency PD detection method was used to characterise PD under square voltages [13, 14]. This technique utilises an antenna to detect the electromagnetic waves emitted during the PD process. One technique that was recently used was measurement using optical detection system that registered the light emitted from every discharge as PD event (Fig. 1). This technique which they referred to as 'optical PD technique' is independent of the load current noise and seems to provide the most reliable information for the evaluation of the PD phenomenon under the square wave voltage source. There result shows that the electrical and optical PDs are well correlated [7].

In this paper, two electrode geometry types in oil insulation have been built for the experimental setup; a point-plane electrode and a sharp edge electrode on the surface of solid insulation. Three voltage types were used; sinusoidal voltage, bipolar slow rise square voltage and unipolar fast rise square voltage. The ‘optical PD technique’ was used to study the PD characteristics of the two geometries under the different voltage types. The goal is to achieve discharge characteristics for each geometry and voltage type and how it affects the integrity of real power equipment/components. The characteristics could be used to identify PDs resulting from such geometries in power equipment and components. All the measured voltage in this work is peak–peak.

2 Experimental

The laboratory experiment was performed in a test cell (pressure vessel). The point-plane electrode geometry was mounted in the pressure test cell. It consists of a tungsten needle shown in Fig. 2 (etched to obtain a tip radius of curvature, rp of ~2 μm) facing a grounded plane. The gap distance was made to be 2.5 mm. The test cell was filled with Nynas Nytro 10X transformer oil. The cell was re-filled with Nynas Nytro 10X transformer oil. The board was metallised at both sides with copper sheet of thickness 420 μm. The metal plate was etched to create a trench of 2.5 mm on the top metallisation layer. Microscopic study shows that the trench has sharp edge of radius of about 2 μm close to the board.

3 Results and discussions

The result from a point-plane gap and the PCB trench in insulating fluid is shown in Figs. 4–9. The figures are pictures from the Omicron measurement system. Fig. 4 shows a typical PD pattern for positive and negative PDs in bulk oil at 26 kV peak–peak applied voltage. The applied voltage was increased by steps of 1 kV with a waiting time of 1 min at each voltage level till initiation of PDs. The inception voltage was considered to be the voltage where the first few PDs occur within the 1 min. The PDIV for sinusoidal voltage was obtained to be 18 kV peak–peak. At this voltage, few small negative PDs were recorded above 1 pc without positive PDs. As the input voltage increases, the number and magnitude of the negative PDs increased. At 22 kV peak-peak, there was further increase in the number of negative PDs and initiation of positive PDs was observed on the second half of the cycle. Further increase in voltage results in increase in the number of both negative and positive PDs. The PD pattern in Fig. 5 was obtained at 26 kV.

Switching the applied voltage to a bipolar square voltage with rise time of 400 μs, produced PDIV of 14 kV peak-to-peak. The PD pattern shown in Fig. 6 was obtained at 18 kV peak-to-peak. Application of square voltage resulted in PDs with higher magnitude as compared with the obtained PDs under sinusoidal voltage. The discharges concentrate on the slope of the square wave. The number and magnitude of discharges increased with voltage increase for the two voltage types.

The voltage was then changed to unipolar square wave voltage with rise time of about 100 ns. This voltage will be referred to as fast rise square voltage in this work. Application of both negative and positive fast rise square voltage led to a sharp decrease in PDIV. PDIV of 8 kV was obtained for the two polarities. As seen in the typical PD pattern obtained at 10 kV in Fig. 7, the discharges due to positive fast rise square voltage was observed to have occupied a narrower region along the slope (as shown with the arrow) compared with the slow rise square voltage.

Changing the test object from point-plane geometry to PCB card shows a shift in the PD pattern for every half cycle under sinusoidal voltage as shown in Fig. 7 with an inception voltage of 14 kV. A comparison of PD pattern (Fig. 8) with what was obtained from point-plane gap (Fig. 4) indicates that the patterns have moved towards 0-crossing for every half-cycle with PDIV
lower than the point-plane electrode. This is a clear indication of
the existence of space charges. These space charges are hetero-
charges remaining from the injection at previous half-cycle. PD
activity will be concentrated at the triple region around the sharp
edges of the high voltage plate due to potential towards the
grounded plate under the PCB board. The electric field at the triple
region is enhanced by the net charge. The electric field stress may
lead to local breakdown at lower voltage compared with point-
plane and PD is initiated.

Changing the applied voltage across the PCB trench to slow rise
square voltage produced a PD pattern in Fig. 9 which is similar to
point-plane pattern in Fig. 6 but with PDIV lower than that of the
point-plane geometry. The decreases in PDIV under similar input
square voltage is an indication that space charges accumulation at
the oil-board interface may be responsible for that. The PDs are
concentrated around the rising and falling slopes of the square
voltage. The use of negative fast rise square voltage is seen to also
produce a lower PDIV compared with what was obtained with
point-plane but positive fast rise square voltage produced PDIV
slightly higher than that of point–plane geometry. This is an
indication that positive PD occur at higher voltage at the triple
region compared with point-plane. Fig. 10 shows a typical PD
pattern of unipolar fast rise square voltage. The appearance of PDs
on the falling slope of the unipolar square voltage can be observed
when compared with that of point-plane where there were no PDs on
the falling slope. The decreasing voltage of the falling slope is not
expected to produce any discharge but an induced reverse electric
field result in the discharges along the falling slope. This discharge
is often called reverse discharge. The charge memory effect of
solid dielectrics that helps in trapping residual space charges on the
solid surface enhance the induced electric field [15]. There is the
possibility of having reverse discharges along the falling slope with
magnitude that can sometime be higher than that of discharges
along the rising slope.

Different voltage waveforms have been seen to have influence
on PD inception and patterns. It will be interesting to compare the
results obtained from point-plane under sinusoidal voltage with the
obtained results under square voltages. The PDs under sinusoidal
voltages were observed to concentrate at the crest and trough of the
waveform with an inception voltage of 18 kV. However, under
square wave voltages, the PDs were observed at rising and falling
slopes of the square wave. The inception voltage seems to be
dependent on the rise time of the square voltage as seen in Fig. 8. The PDIV for slow rise and fast rise square voltages are 14 and 8 kV, respectively, for point-plane. The PD is contained between the PD inception time and the time when the voltage reaches maximum. This is referred to as PD time range [7, 16]. The rise time of the applied voltage influenced the inception time. The lower the rise time, the lower the PD time range. The PD formation processes under square voltage may likely be dominated by voltage rise time over hetero-charges. This may have led to the higher magnitude of PDs under fast rise square voltage as shown in Fig. 10.

The maximum PD amplitude at inception is higher for square voltages compared with sinusoidal voltage. For point-plane, the PD magnitude at inception increase from about 1.5 a.u. for sinusoidal voltage to 3 a.u. (arbitrary unit) for all square voltages. This increase may be due to the rise time of square voltages. Meanwhile, the PD magnitude at the triple junction of the PCB trench appears to be high compared with the point-plane geometry for slow rise voltage and fast rise square voltage. Comparing the PDIV and PD magnitude of negative and positive fast rise voltage in Figs. 11 and 12, it is observed that while negative PDs occurred at lower voltage compared with positive PDs, the positive PD magnitude is twice that of negative PD at inception.

Electric field distribution for the two geometries was calculated using COMSOL Multiphysics, a software based on finite element method since the PD phenomenon process is initiated with electric field enhancement. The plot from the calculation of the electric field distribution of the two different electrode geometries is shown in Figs. 13a and b. Fig. 13a indicates that electric field strength is maxima at the tip of the point electrode with a maximum electric field of about 80 kV/mm when voltage of 6.5 kV was applied. On the other hand, application of electric field on the PCB card produced maximum electric field strength at the triple junction region of the high voltage copper plate, liquid and the board interface as shown in Fig. 13b. The triple junction for PCB model has maximum electric field of 130 kV/mm with voltage of 6.5 kV applied. This enhanced field at these regions can lead to ionisation of the liquid within the region if the field strength is higher than the breakdown strength of the liquid. This will result in local breakdown also known as PDs. The triple point region of the PCB has a higher field compared with the tip of the point electrode. This account for the reason why the 2.5 mm trench on the PCB has lower PD inception compared with same gap for point-plane electrode system.

The relative position of maximum electric field stress within the triple point region is a function of both the permittivity of the solid material and the configuration of the geometry.
Fig. 8  Optical PD pattern on PCB trench in mineral oil under sinusoidal voltage at 50 Hz

Fig. 9  Optical PD pattern on PCB trench in mineral under bipolar slow rise square wave voltage

Fig. 10  Optical PD pattern on PCB trench in mineral oil under unipolar fast rise square voltage
insulation and that of the insulating fluid. With the relative permittivity of the solid insulation higher than the insulating fluid as it is in the PCB-mineral oil system, the board attracts the discharges towards the surface due to charges. The discharges are then most likely pulled towards the board and become surface discharges by settling along the board interface parallel to the applied field. At higher voltages, PDs of larger amplitude were observed. These PDs may be associated with creepage along the board surface. Further increase of the applied voltage beyond this point may lead to streamers that could bridge the trench, leading to breakdown.

A number of factors can influence electric field enhancement at the high field region. Under high voltage, charge injection could result in localise Joule heating, and leading to a partial vaporisation. Continuous heating process could cause a rise in the liquid temperature. This could exceed the boiling temperature under a long duration and molecular evaporation may occur. This could lead to internal generation of gases resulting in gaseous bubble in the liquid.

4 Conclusion

The results revealed that voltage slew rate dominates over other factors that influence PD inception and magnitude. Fast rise square voltage has the lowest PDIV while the sinusoidal voltage has the highest. This is due to the presence of homo-charges which shield the electrode from early inception of PDs when sinusoidal voltage was applied. Numerical calculation revealed that the presence of impurities such as air and moisture has influence on field enhancement at the triple region. From the sharp deviation of PD behaviour under sinusoidal and square voltage, the idea of using sinusoidal voltage for factory acceptance test (FAT) for power equipment or components that operates on fast rise pulse voltage may not produce the results that exhibit the true state of the power
equipment/component under test. Developing test methods based on operating voltage will make such FAT results more reliable.

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6 References

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