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Influence of Fast Rise Voltage and Pressure on Partial Discharges in Liquid Embedded Power Electronics

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ABSTRACT

Initiation of partial discharges at the highly stressed regions of an Insulated Gate Bipolar Transistor (IGBT) can lead to degradation of the insulation and eventual total breakdown of the system. In this work, an experimental setup has been designed for the study of partial discharges (PDs) under different voltage waveforms. PD behavior of IGBT insulation was investigated using conventional and optical techniques. Influence of pressure and voltage wave shape is documented. The test environment was first characterized with point-plane geometry under sinusoidal and slow rise square voltage of up to 20 kV_{peak} and fast rise square voltage of up to ±50 kV. The measured electrical and optical PDs showed good correlation, revealing that optical PDs can be relied on for the characterization of PD phenomena. High slew rate of the square voltage reduced the inception voltage and increased magnitude. The PD pattern from the trench shows the existence of space charges. The PDs which occurred within the triple point region are most likely attracted along the board interface and become surface discharges. Pressure suppresses the initiation and propagation of the discharge.

Index Terms — **Power electronics, dielectric liquid insulation, partial discharge, voltage waveform, rise time, space charges, pressure.**

1 INTRODUCTION

THE depth for exploration of oil and gas at subsea is increasing to several thousand meters. The pumping technology utilizes motors with electronic variable speed drivers (VSD) which is also referred to as variable frequency drivers (VFD). The voltage-source, pulse-width modulated (PWM) frequency converter is the most common form of VFD [1]. The available motors in the market are rated for 3.5 MVA. An increase in water depth will require rated power of more than 6 MVA. Today's converters are located in 0.1 MPa (1 bar) cubicles with conventional technology. As the converter rating increases and design depth increases, the vessel becomes bulky with thick wall to compensate for the pressure difference, causing poor cooling [2]. Therefore new technology is required for oil and gas exploration at subsea up to the depth of 5000 m. This brings about the quest for the development of less expensive and more manageable pressure compensated vessels and penetrators for subsea application. Such vessels will have significantly reduced weight for subsea depths and better cooling. This brings about the development of pressure tolerant power electronics for subsea operation. The power electronic module contains critical components such as power semiconductors, DC-link capacitors and drivers. The electronic converter contains transistors that deliver power to the motor. The common choice of transistor for modern VFD is the "Insulated Gate Bipolar Transistor" (IGBT). It utilizes "pulse width modulation" (PWM) to simulate a voltage sine wave at the desired frequency to the motor [3]. Satisfactory operation of these critical components in high pressure environment could make this achievable.

Silicone gel is the most widely used material for encapsulation of power electronic circuits. But non-reversible electrical degradation of gel calls for optimization of insulation design [4]. The electronic module needs to operate in an incompressible insulating material that will serve as heat transportation medium and prevent electrical discharges in the module.

Liquid-based insulation system seems to be one obvious candidate from the listed specifications [5].

The electronic power converter module consists of the power semiconductors (IGBT, diodes), inter-connections and

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much more. There is high electric field stress at edges of the semiconductors and the metallization along the trench at the top of the ceramic substrate. These stresses result from unipolar switching in the range of 6.5 kV. Aluminum Nitride (AlN) is often used as substrate material. At not too high voltage, partial discharge initiation can occur due to divergent field. Embedding IGBT modules in liquid will protect the component and prevents electrical discharges. Simulation of electric field distribution shows that the highest stress region in the trench is at the triple points where the metal, substrate, and liquid meet, labelled A and B in Figure 1 [6]. Potential of the conductor under the substrate will also influence the divergent field at point A and B.

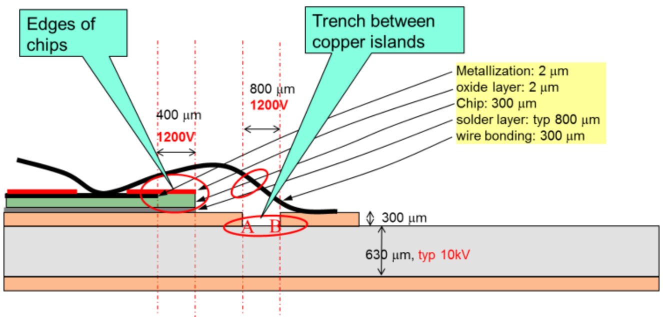

Figure 1. High stress regions on a power electronic module.

The electrical degradation of gel due to its non-self-healing property brings about the need to investigate the possibility of operating power electronics in only liquid filled environment. No application specific test methods exist for voltage endurance test for liquids in power electronic geometries [8]. The actual voltage conditions in IGBT modules are composed of dc and step voltage with short rise time. It has been shown that sinusoidal voltage is not representative of the actual voltage to evaluate the behavior of solid insulation in IGBT module [7]. Partial discharges (PDs) in liquid vary as you switch from sinusoidal to square wave due to various factors. That is one of the reasons why PDs obtained from sinusoidal voltage is not sufficient to evaluate the behavior of PDs on IGBT module. But measuring electrical PD at high dU/dt is accompanied by noise of high amplitude. This also brings about the need for the development of test methods to study power electronic stresses. The performance of different dielectric liquids needs to be evaluated in a relevant model to determine the liquid that is more suitable for use for the power module.

A paper on partial discharges on AlN shows that it is electroluminescent and may contain voids [9]. It produces light at voltages below partial discharge inception voltage (PDIV). This makes AlN unsuitable for optical partial discharge studies in liquid. Printed circuit board (PCB) on the other hand is non-electroluminescent and has low cost. That makes it a good candidate as a model of IGBT baseplate for the study of liquid performance. A model of gaps in high voltage power electronics on PCB is suitable for the study of partial discharges in the narrow gap between high voltage and low voltage electrodes. Since the high amplitude noise will not won't allow qualitative conventional PD measurement at high slew rate (dU/dt), an alternative technique is to explore the possibility of light emission measurement using photomultipliers.

The aim of this work is to develop an experimental setup to study the nature of partial discharges in IGBT insulation under pressure and high dU/dt. The study object was a trench between metal surfaces of a PCB model embedded in insulating liquid in a pressure vessel under different voltage shapes. This was done under sinusoidal voltage, slow rise bipolar square voltage with rise time of about 400 µs, and fast rise unipolar square with rise time of about 100 ns. All the voltages were at 50 Hz. Pressure was varied from 0.1 MPa to 10 MPa (1 to 100 bar).

2 SPACE CHARGE PHENOMENA IN DIVERGENT FIELD

The enhancement of local field near an electrode edge may result in local breakdown otherwise known as partial discharges (PD). High electric field at the electrode edge generates free space charges in the liquid surrounding the edge. The generated charges accumulate in the liquid around the triple region and distort the field distribution affecting the PD inception voltage. When charge (homo-charge) is injected in the liquid, it is transported away from the high field region. This charge will reduce the edge field during the first half cycle, thus decreasing the probability of PD inception. In the subsequent second half of the power cycle where polarity reversal occurs, the electrode will inject charge of opposite polarity. The earlier injected homo-charges become hetero-charges and then enhance the field in front of the tip. When there is a large amount of charge in the liquid from the previous positive half cycle, the homo-charges that are newly injected remain within the high field region counteracting the influence of the hetero-charges [10]. The forces on the homo-charges dominate as the field within the vicinity of the electrode edge is higher than the field further away around the hetero-charges. The space charges are attracted to the surface of the solid insulation since the relative permittivity of the solid insulation is higher than that of the insulating fluid. Some of these charges are trapped at the surface and cannot move across the barrier. The total electric field is changed by these space charges reducing the probability of PD inception.

After the occurrence of PD, voltage drop occur on the discharge channel. At relatively low voltage, the field at the sharp edge might not be large enough to sustain ionization of the liquid molecules and the PD will disappear. Above a critical voltage, further ionization of the liquid molecules at the high field region is sustained and propagation of streamers occur [11, 12].

3 EXPERIMENTAL SETUP

3.1 POINT-PLANE TEST

Point-plane geometry has a known and well documented behavior. Pre-breakdown events in liquids under point-plane have been extensively studied under DC, AC and impulse

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voltages using shadow photography [13-16]. This work utilized point-plane geometry to verify and calibrate the setup. It was also used to qualify the optical PD recording. The point-plane electrode geometry was mounted in the pressure test cell to record PD behavior under different voltage sources. It consists of a tungsten needle (tip radius of curvature, r_p of about 2 µm) facing a grounded plane. The gap distance was made to be 2.5 mm similar to the PCB trench gap. The maximum field at the tip of the needle in liquid was calculated to be 121 kV/mm at 10 kV_{peak} ac.

3.2 TEST BOARD

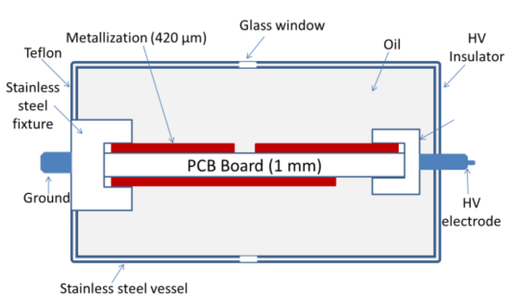
A model of baseplate for HV power electronics was produced using PCB. The PCB card as shown in Figure 2 has dimension 38 mm × 24 mm × 1 mm. The board was metallized at both sides with copper sheet of thickness 420 µm. There exists a trench of 2.5 mm through the top metallization layer. The sharp edge was measured to have a radius of about 2 µm. The maximum field at the sharp edge within the triple region in liquid was calculated to be 254 kV/mm at 10 kV_{peak} ac. The field is higher than point-plane geometry due to field enhancement.

A. PCB card with trench

B. The trench from the microscopic image of sliced test object

Figure 2. PCB Test Object.

A: Pressure Vessel



B: Internal Structure

Figure 3. Pressure test cell.

3.3 TEST CELL

Figure 3A shows the photo of the bespoke pressure test cell for PD measurement. Figure 3B describes the internal structure of the test cell with the test object inside it. It was specifically designed to avoid PD within the test cell. The pressure vessel was designed to withstand pressure of up to 15 MPa (150 bar). Two suitable fixtures were made from stainless steel to fix the board in the pressure test cell. One of the fixtures connects the HV plate of the board to high voltage source and the other connects the low voltage plates of the board to the PD measurement system.

The pressure of the liquid inside the vessel was generated with a pressurization system that uses a piston. It is manually controlled and can produce pressure up to 10 MPa (100 bar).

3.4 MEASUREMENT SETUP

This setup shown in figure 4 is designed to investigate the nature of partial discharges along the trench of the test sample in the bespoke pressure vessel under sinusoidal voltage, slow rise bipolar square voltage and fast rise unipolar square voltage.

The sinusoidal voltage and slow rise bipolar square voltage with rise time of 400 µs was produced with TREK 20/20-HC high voltage amplifier which has maximum output of 20 kV_{peak}, maximum current of 20 mA peak AC, and maximum frequency of up to 20 kHz. A coupling capacitor (1700 pF) was connected parallel to the HV source between the source and the test cell.

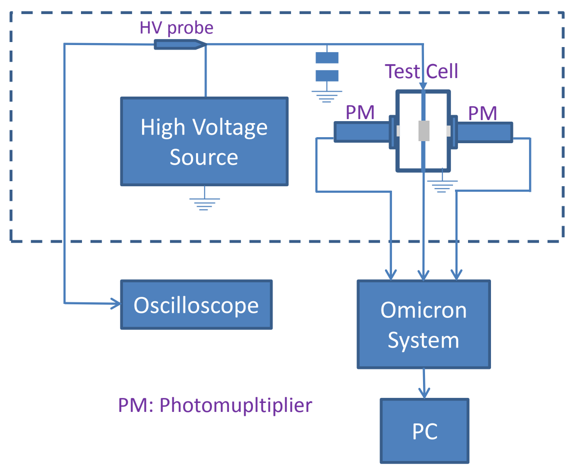


Figure 4. Experimental Setup with HV Source.

Fast rise unipolar square voltage with rise time of 100 ns was produced with laboratory-built high voltage pulse generator capable of supplying pulses of short rise time of either positive or negative polarities up to 50 kV. The high voltage source consists of two dc sources charging two capacitor banks, and a fast, bipolar transistor switch coupled between these two capacitors and the high voltage output. It could operate with switching frequency up to 1 kHz. This gives the possibility of using a fixed DC offset and pulse amplitude given by the voltage difference between the two dc sources. There is a limiting resistor between the transistor switch and test object to limit the current to 30 A, the

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maximum peak current the switch can handle. The limiting resistor also controls the rise time of the voltage across the sample. The switch is controlled by 5 V TTL pulses. The HV pulses could be negative or positive. The high voltage source was connected to the test object and the low voltage side of the test cell was connected to the measuring impedance of the measuring system. Great attention was paid to the background noise and effort was made to reduce background noise to the barest minimum. Careful grounding and shielding of the system was ensured.

The test objects were fixed in the pressure test cell. The cell was filled with Nytro 10XN mineral oil after it had been evacuated. All experiments were performed under 50 Hz, at ambient temperature.

3.5 PHOTOMULTIPLIERS

Photomultipliers (PM) (Hamamatsu R2055) were used to record the weak light emission from the partial discharge. The supplied voltage between the anode and cathode was 1250 V. The gain for the PMs is in the range from 2.0×10^6 to 3.75×10^6. Two photomultiplier tubes were fixed on the windows of the test cell and connected to the measurement system.

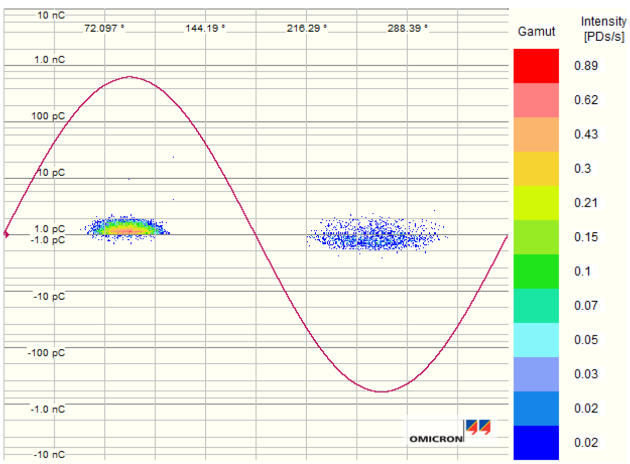
3.6 PD DETECTION

An Omicron PD detection system was used to measure the partial discharges. The low voltage end of the test cell was connected to the Omicron system. The detector for electrical PD was calibrated with 10 pC charge from a calibrator. The background noise of PD measurements was below 0.5 pC. The detection threshold of measurements was fixed to 1 pC.

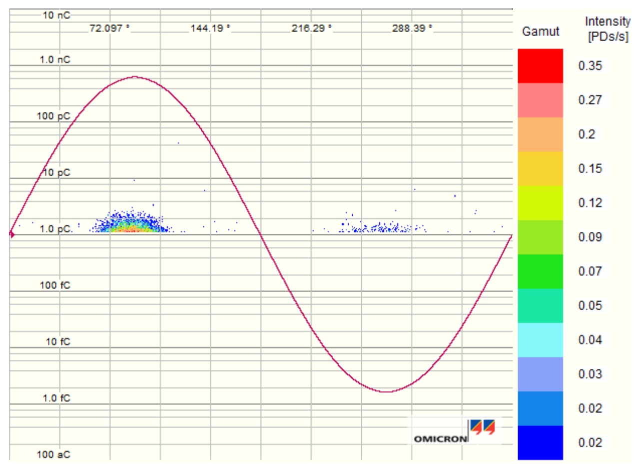
The photomultiplier was also connected to the Omicron system. The detector for light discharge was not calibrated as there is no standard yet for the calibration of light detection. Proper shielding with Faraday cage reduced the background noise from electromagnetic interference. The detection threshold of measurements was fixed to 1 pC.

The duration of PD recording at each voltage level was 1 minute for point-plane geometry and 3 minutes for trench. The quoted experimental values for number of PDs are average of three readings. The PD magnitude as used in this work is the maximum value of discharge recorded in pC.

4 POINT-PLANE IN LIQUID UNDER DIFFERENT VOLTAGE SHAPES

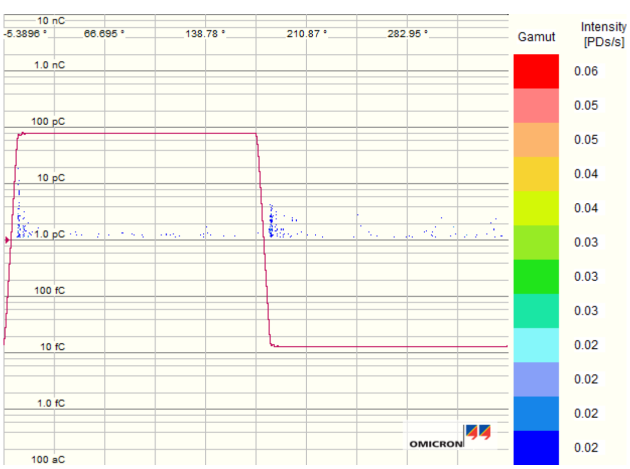


A. Electrical PD pattern at 26 kV

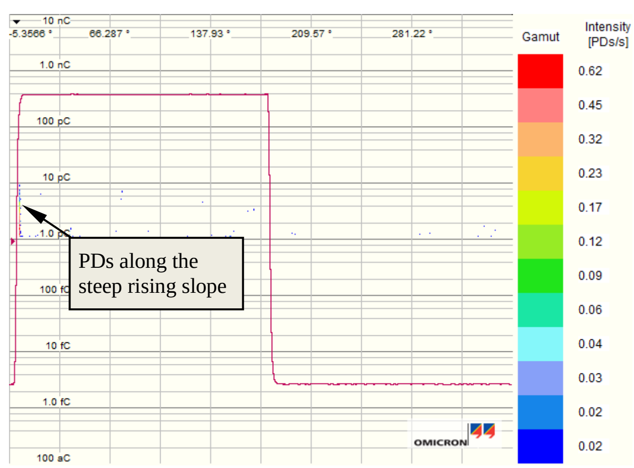


B. Optical PD pattern for sinusoidal voltage at 26 kV

Figure 5. Electrical and Optical PD Pattern in Mineral Oil Under Sinusoidal Voltage at 50 Hz.



A. Optical PD pattern for slow rise square voltage at 18 kV



B. Optical PD pattern for fast rise square voltage at 10 kV

Figure 6. Optical PD Pattern in Mineral Oil Under Square Voltage at 50 Hz.

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The behavior of PDs in liquid varies as you switch from sinusoidal to square wave. Space charges, electrode geometry and rise time of the square voltage has significant influence on the nature of PDs.

4.1 COMPARISON OF OPTICAL AND ELECTRICAL PARTIAL DISCHARGE

The electrical and optical PD patterns recorded with the point-plane gap at different voltage shapes at 50 Hz are shown in Figures 5 and 6. The curvature of the tip of the needle influences PD inception. The PDIV for PDs greater than 1 pC for sinusoidal voltage was found to be 18 kV. At this voltage, few small negative PDs just above 1 pC were recorded. The number and magnitude of the discharges increased with voltage. Positive PDs was observed from 22 kV.

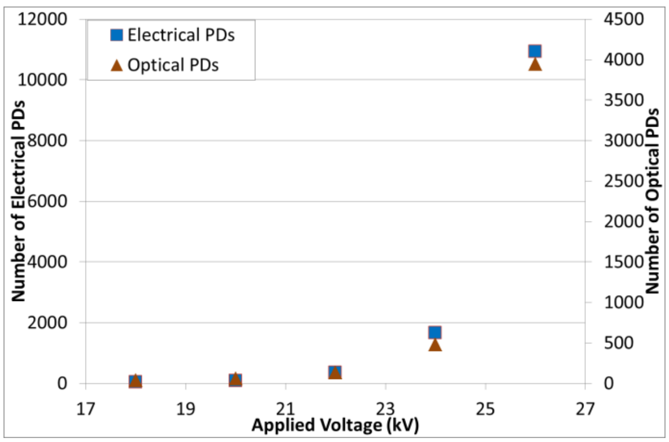

Figure 7. Plot of Number of PDs versus applied voltage.

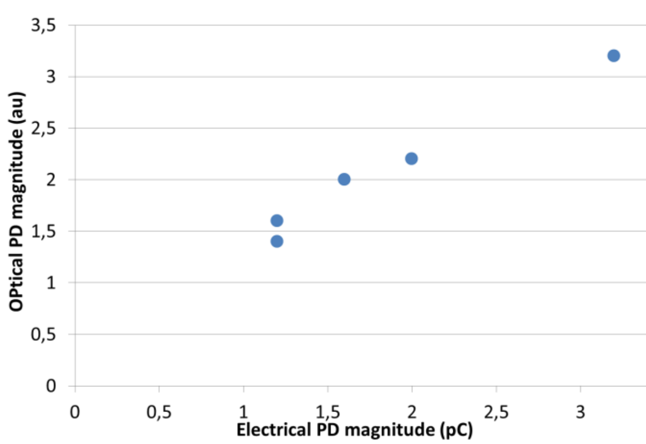

Figure 8. Correlation between electrical and optical discharge.

The local breakdown produced weak light which was detected by the photomultiplier and recorded as optical PD. Figure 5A and B shows the comparison of recorded electrical and optical PD at 26 kV. The detected electrical and optical PD is plotted vs. crest voltage in Figure 7 to examine the correlation between the set of PD measurements. The magnitude of electrical and optical discharges as seen from the plot in figure 8 has linear correlation. Therefore, optical PD can be considered practical for the evaluation of PDs in mineral oil. The unit of pC was adopted to quantify the recorded optical PD magnitude in correlation with the recorded electrical PD.

The PDIV for slow rise bipolar square voltage of 400 µs rise time was obtained to be 14 kV as shown in Table 1. At this voltage, few optical PDs were observed. The PDs from the square voltage are larger compared with PDs seen under sinusoidal voltage. The discharges were observed to concentrate on the slope of the square wave as seen in Figure 6A and B. The number and magnitude of discharges increased with voltage.

Table 1. Optical PDIV for different voltage sources.

Voltage source	PDIV (Pk-Pk)
Sinusoidal Voltage	18 kV
Bipolar square voltage, t_r 400 µm	14 kV
Unipolar positive square voltage, t_r 100ns	8 kV
Unipolar negative square voltage, t_r 100 ns	8 kV

When the rise time was changed to 100 ns at 50 Hz, a sharp decrease in PD inception voltage was observed. PDIV for both negative and positive fast rise unipolar square voltage was obtained to be 8 kV. Table 1 shows the optical PDIV for various voltage sources at 50 Hz. PDs under the fast rise unipolar square voltage have higher magnitude at the same crest voltage. While PD of 1.4 pC magnitude was recorded at inception voltage for sinusoidal voltage of 18 kV, PD of magnitude 10 pC was obtained at 18 kV slow rise bipolar square voltage and PD of 9 pC was obtained at 10 kV fast rise positive unipolar square voltage.

As can be seen from Figure 6, there is no discharge during the falling period of the slow and fast rise square voltages as was observed by Liu et al [17] in a 50 mm needle-plane gap. It may be that there are insufficient residual space charges to induce the reverse electric field to cause reverse discharge along the falling slope of the square voltage.

4.2 DISCUSSION ON PD IN POINT-PLANE

The point-plane geometry in the pressure test cell is a test to qualify the performance of the measuring test setup and instrumentation, checking noise levels, sensitivity and calibrating the optical PD detection using a well-documented geometry. It is also a preliminary investigation to evaluate the influence of voltage rise time on PD inception and magnitude. The behavior of point-plane is well documented. A local strong electrical field occurs at relatively low voltage and the location of PD events can easily be located using optical method. We found that the set-up worked well with low noise (< 1pC) mainly coming from the HV-amplifier. Optical detection seems to work well in transformer oil.

Partial discharges are initiated at 18 kV under sinusoidal voltage. Increase in voltage leads to increased number of discharges.

PD patterns are known to be influenced by different waveforms. It is interesting to compare the results obtained from point-plane under sinusoidal voltage with the obtained results from square wave voltages. While the PDs observed at sinusoidal voltages concentrated at the crest and trough of the waveform, PDs under square wave voltages were observed at

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rising and falling slopes of the square wave. 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 [18]. The time range and the inception time are influenced by the rise time of the applied square wave voltage. The lower the rise time, the lower the PD time range. The slow rise bipolar square voltage produced hetero-charges and yet the fast rise unipolar gives larger PD. This suggests that PD formation processes is dominated by voltage rise time over hetero-charges. As seen from Figure 9, PD magnitude increases with voltage increase with fast transient voltage producing larger PDs.

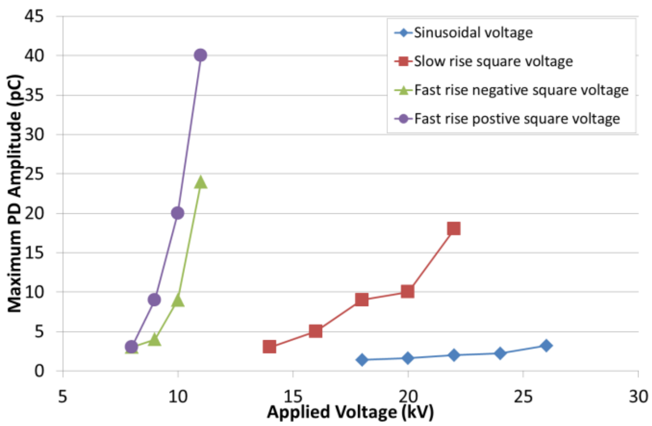

Figure 9. PD for different voltage sources.

5 PD IN THE TRENCH OF PCB MODEL

The PCB test object was fixed in the pressure test cell. Sinusoidal voltage, slow rise bipolar square voltage, fast rise positive unipolar square voltage and fast rise negative unipolar square voltage were applied. The pressure of the liquid was varied from 0.1 to 7 MPa (1 bar to 70 bar). PDs larger than 1 pC were recorded. The two photomultiplier tubes were set to coincidence to avoid detecting dark current from the PMs. Only signals that occurred simultaneously in both PM's were logged. The duration of PD recording at each voltage level was 3 minutes. All experiments were performed at ambient temperature.

5.1 PD IN THE TRENCH

A comparison of electrical PD pattern (Figure 10) recorded with the PCB trench under sinusoidal voltage [6] with what was obtained from point plane gap Figure 5A indicate that the patterns have moved towards 0-crossing for every half-cycle. This is a clear indication of the existence of space charges. These space charges are heterocharges 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 net charge enhances the electric field at the triple region. The electric field stress may lead to local breakdown and partial discharge is initiated.

The relative position of maximum electric field stress within the triple point region is a function of both the permittivity of the solid insulation and that of the insulating fluid. With the relative permittivity of the solid insulation higher than 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. The velocity of the streamers on the PCB surface will depend on the applied voltage. At higher voltages, PDs of larger amplitude were observed. These PDs may be associated with creepage along the board surface. Increasing the voltage beyond this point may lead to streamers that could bridge the trench, leading to breakdown.

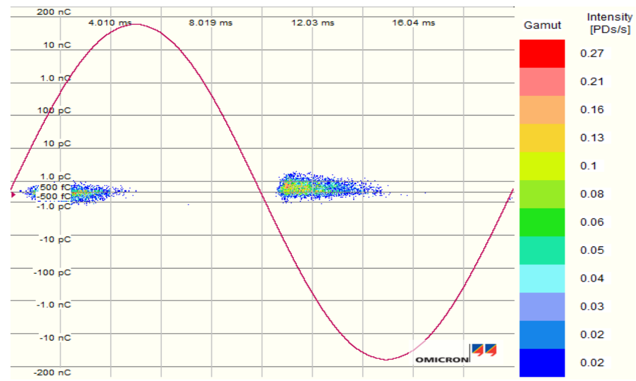

Figure 10. Typical PD pattern on PCB trench under sinusoidal voltage measured electrically.

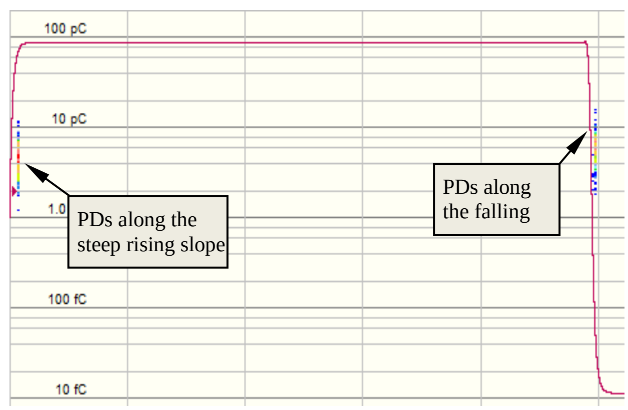

Figure 11. PD pattern on PCB trench under fast rise square voltage.

The behavior of discharges at the PCB interface can be explained with the method of images for interfaces with different permittivity. The electric field from the image charge in the PCB which is proportional to the difference between the permittivity of the mineral oil and PCB, $(\varepsilon_{PCB} - \varepsilon_{Oil})$ is assumed to produce the force on the discharges at the PCB interface. If $\varepsilon_{PCB} - \varepsilon_{Oil} > 0$, the electrical force pulls the discharges towards the interface. But if $\varepsilon_{PCB} - \varepsilon_{Oil} < 0$, the surface (image charge) repels the free volume charge in the oil, regardless of charge polarity [15].

5.1 PD IN THE TRENCH AT 1 BAR

Partial discharge inception voltage along the trench is 13 and 12 kV peak under sinusoidal voltage and slow rise square voltage, respectively. Under the fast rise unipolar square wave voltage, the partial discharge inception occurred at 7 and 9 kV for negative and positive voltages respectively.

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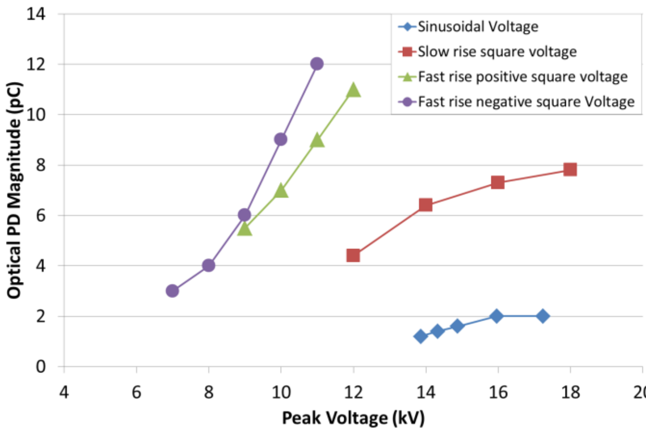


Figure 12. PD Magnitude versus peak voltage along the trench at 0.1 MPa (1 bar).

Unlike in the point-plane geometry, there is discharge during the falling period of the fast rise square voltages as shown Figure 11. Increase in voltage led to an increasing number and magnitude of the discharges. Figure 12 shows a graph displaying variation of PD magnitude with respect to voltages from the different sources. Fast rise negative square wave voltage has lower partial discharge inception voltage (PDIV) and higher PD magnitude. The rate of increase in the PD magnitude with respect to voltage is higher for steeper voltage rise. At 12 kV fast rise negative square voltage, large PD with magnitude of 140 pC was observed. This may have resulted from surface creepage and further increase in voltage may result in further development of streamers that could cross the trench to cause breakdown.

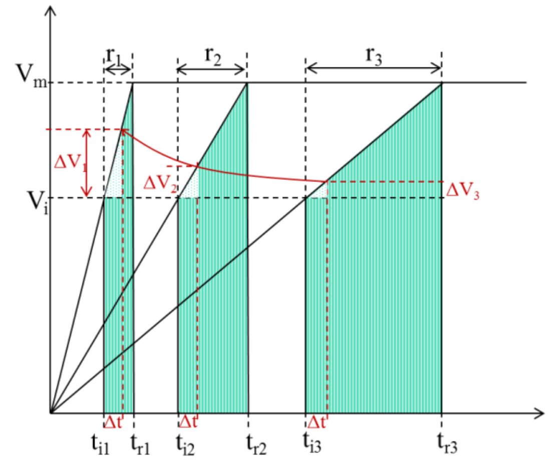
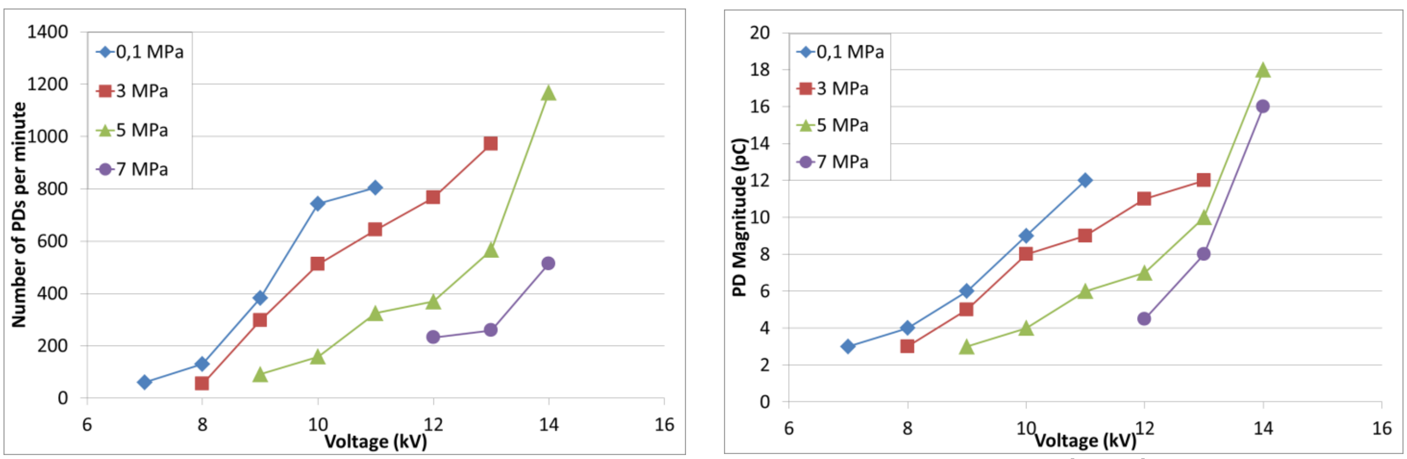


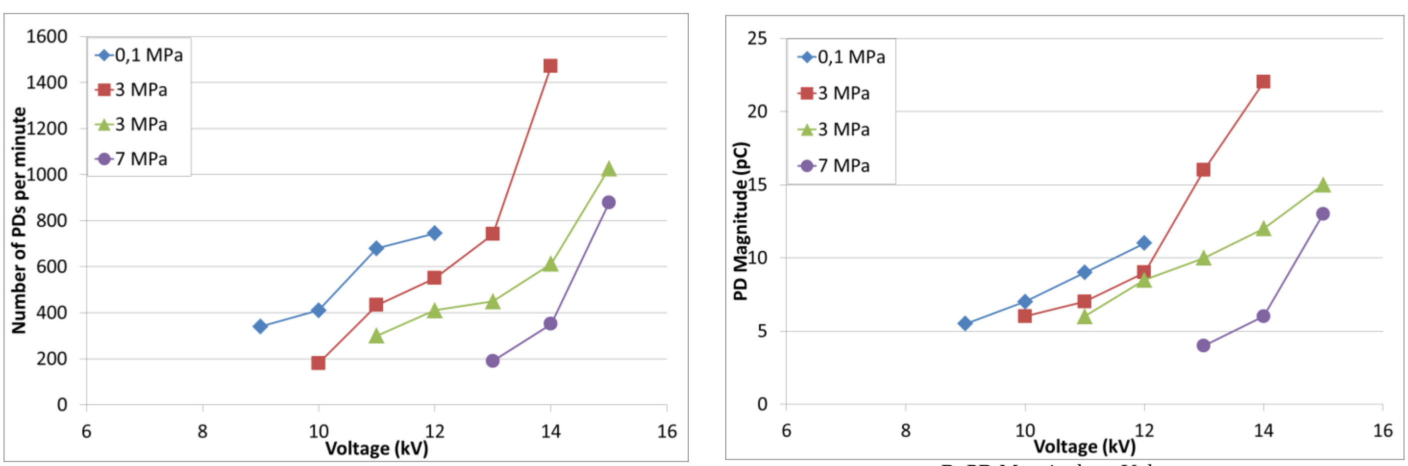
Figure 13. Simplified PD Model.



A: PD rate vs Voltage

B: PD magnitude vs Voltages

Figure 14. Effect of Pressure on PD activity at negative fast rise unipolar square voltage.



A: PD rate vs Voltage

B: PD Magnitude vs Voltage

Figure 15. Effect of Pressure on PD activity at positive fast rise unipolar square voltage.

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The low PDIV and higher PD magnitude under fast rise unipolar square voltage compared with the slow rise bipolar square voltage is probably connected with the high slew rate of the pulse. Consider a Laplacian field i.e. no space charge and assume same inception for all voltage shapes. Supposing the inception voltage *Vi* occurs at time t_i and the voltage reaches maximum (V_m) at time t_r, the slew rate is $\frac{dV}{dt} = \frac{V_m - V_i}{t_r - t_i} = \frac{\Delta V}{\Delta t}$, where Δt, the time lag is equal for all slew rates [16]. Δt represent the discharge propagation time in a liquid. From the relation, ΔV, the driving voltage behind discharge will become higher as slew rate increases as shown in the simplified PD model in Figure 13. The increase in the driving voltage behind PD leads to increase in the magnitude of the discharge as illustrated in Figure 13. Higher slew rate as in the case of fast rise square voltage implies a higher ΔV and consequently a discharge propagating further with a larger charge. As long as the discharge channel has not collapsed, and the voltage is above the stopping voltage the discharge will continue to grow [12].

The discharges along the falling slope often called reverse discharge occur due to induced reverse electric field. This reverse electric field is enhanced by the charge memory effect of solid dielectrics which helps in trapping the residual space charges on the surface [17]. The magnitude of reverse discharges along the falling slope can sometime be higher than the magnitude of discharges along the rising slope.

5.2 EFFECT OF PRESSURE ON PD IN THE TRENCH

Pressure led to a decrease in PD activity. Unipolar fast transient voltage had lowest inception voltage and produced PDs of large magnitude. But as observed from the results, the number and magnitude of PDs decreased systematically as the pressure of the liquid in the test cell increased as shown in Figure 14 and 15. The PD inception voltage increased with increase in the pressure of the liquid as shown in Figure 16. The PD magnitude as seen from Figure 17 was greatly influenced by pressure. At 12 kV fast rise negative square voltage, large PD with magnitude of 140 pC was observed at pressure of 0.1 MPa (1 bar). Increasing the pressure to 3 MPa (30 bar) reduced the magnitude to 11 pC and reduced it further to 4.5 pC at 7 MPa (70 bar).

The same was not observed for fast rise positive square voltage. The observed PD magnitude as seen from Figure 17 was 11 pC at 12 kV and 0.1 MPa (1 bar). This decreased to 3 pC when the pressure was increased to 5 MPa (50 bar).

The pressure dependence of the magnitude and number of PDs under different voltages is shown in Figures 14, 15, 16 and 17. The result is in agreement with earlier reports [20-22]. The results indicate the involvement of a gas phase process during the developmental stage of the discharges. Pressure suppresses the magnitude and rate of partial discharges. Streamer propagation length is known to increase with increase in voltage. Increase in pressure may have led to collapse of the streamers while propagating. This process may have stopped the streamer propagation due to break in the conduction path. This will limit the discharge process and hinder streamers from moving across the trench, reducing the chance of breakdown [22, 23].

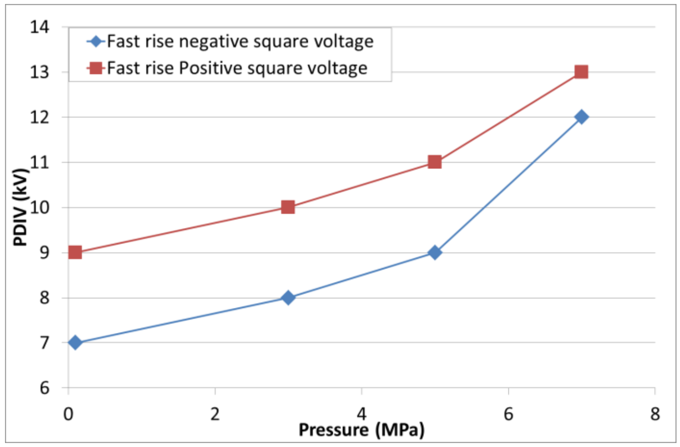

Figure 16. Effect of Pressure on PDIV.

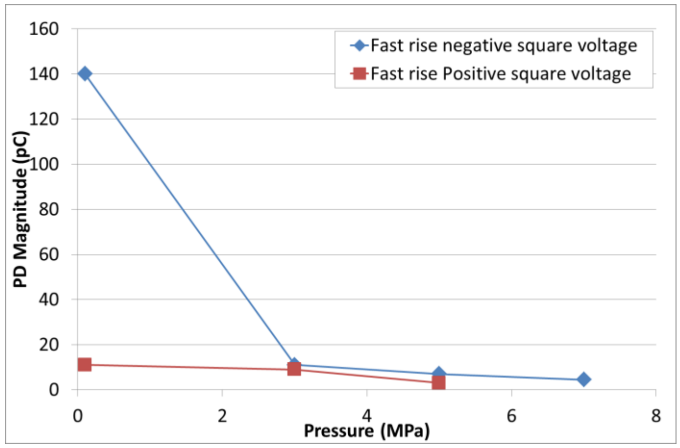

Figure 17. Effect of Pressure on PD Magnitude at 12 kV

6 CONCLUSION

A working partial discharge setup has been developed with capability of varying pulse slew rate. The optical PD detection system was successfully utilized to record partial discharges from under various voltage shapes. There exists good correlation between the recorded electrical and optical PDs in mineral oil. The obtained results demonstrated that optical PD detection is a reliable technique for the measurement of PD under fast transient voltages.

The results revealed that voltage slew rate dominates over other factors that influence PD inception and magnitude.

Under some but not all voltage shapes, reverse discharges occurred along the falling slope due to charge memory effect of solid dielectrics which helps in trapping the residual space charges on the surface. The magnitude of the reverse discharges was sometimes observed to be higher than the magnitude of the discharges on the rising slope. This indicates that the space charges produced at the idle state of IGBT modules can influence PD in the system.

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Pressure increase suppresses PD activity thereby leading to increase in PD inception voltage and reduction in PD magnitude as well as the PD rate. The influence of pressure on the magnitude of the PDs is very significant as large PD produce at 0.1 MPa (1 bar) under negative fast rise unipolar voltage was suppressed to 9 pC when the pressure was increased to 3 MPa (30 bar). While streamer propagation is determined by electrical properties of the liquid and high voltage level and shape, pressure on the other hand collapses the propagation of the streamers.

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