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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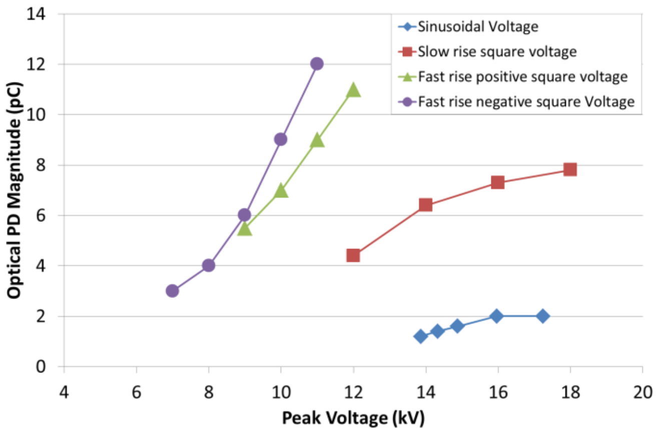


Figure 12. PD Magnitude versus peak voltage along the trench at 0.1 MPa (1 bar).

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.

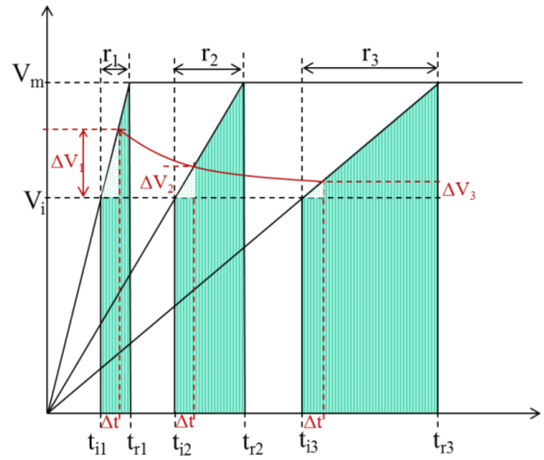
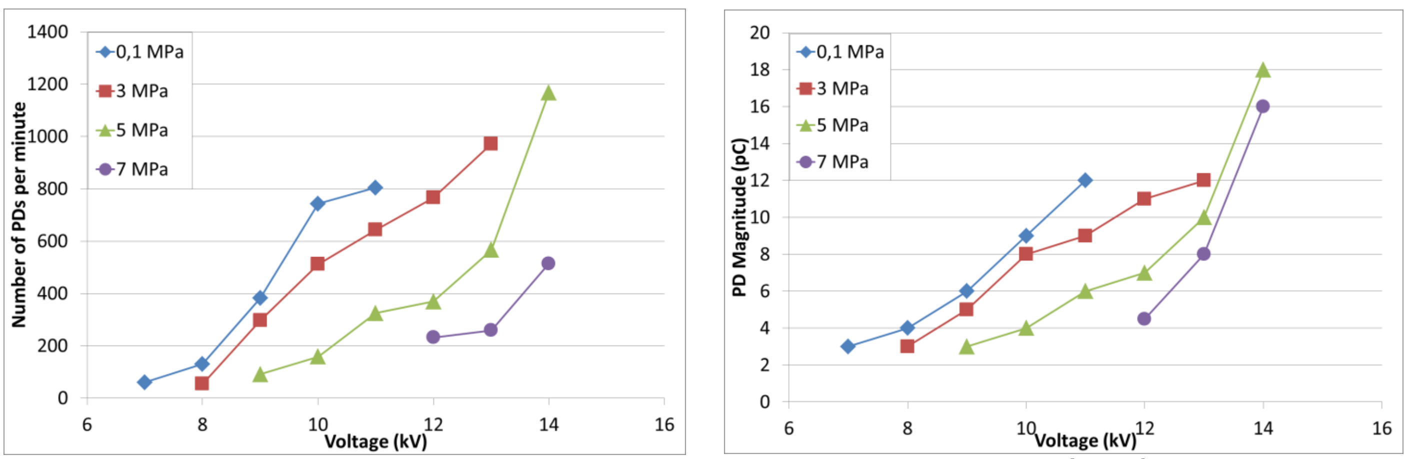


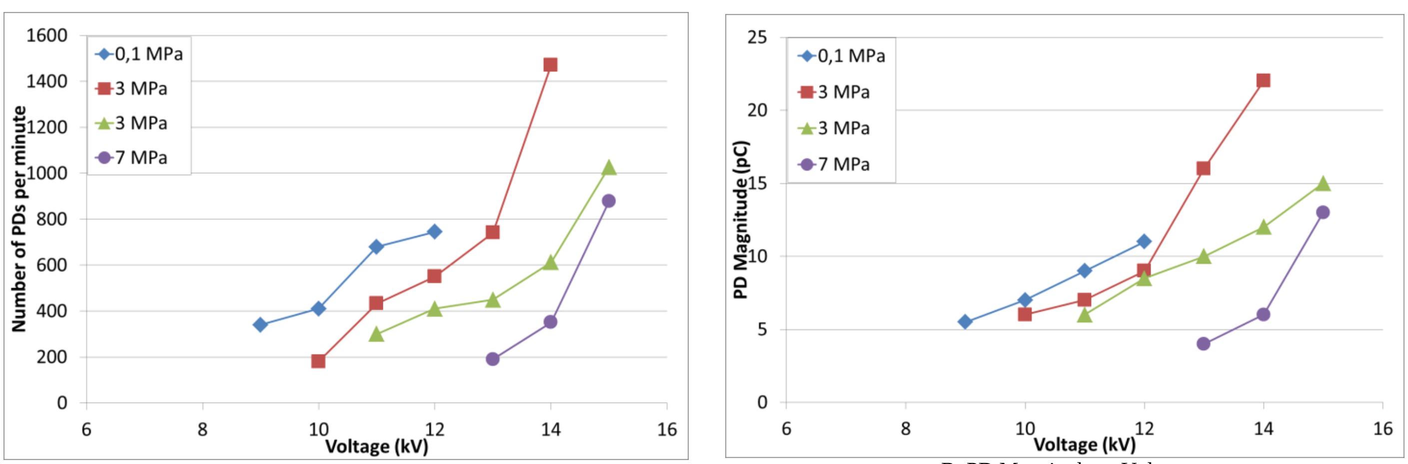
Figure 13. Simplified PD Model.



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.

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].

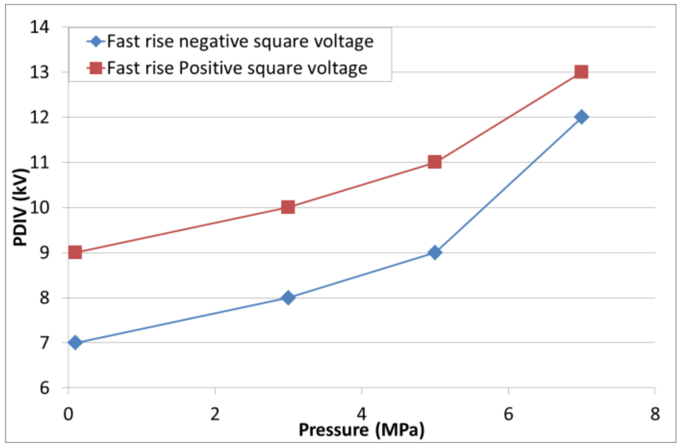


Figure 16. Effect of Pressure on PDIV.

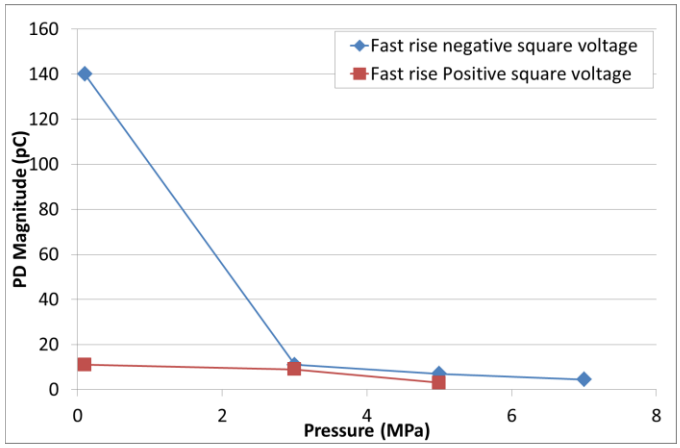


Figure 17. Effect of Pressure on PD Magnitude at 12 kV

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.

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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