Partial Discharges in Narrow Gaps on Power Electronic Converter

A.A. Abdelmalik, A. Nysveen,
Norwegian University of Science and Technology
Department of Electric Power Engineering
Trondheim, Norway

L. Lundgaard
SINTEF Energy Research
Electric Power Technology
Trondheim, Norway

Abstract- **The quest for power electronic converters to operate in a subsea pressurized environment that is completely filled with appropriate dielectric liquid brings about the need to study the insulation performance of liquid in the system while in operation. One of the critical regions for electrical insulation is the trench between metallization edges of the power converter. These regions are susceptible to high electric field stress and electrical discharges can be initiated around the region which could lead to insulation deterioration and eventually breakdown. This paper presents an experimental setup for the study of partial discharges (PDs) along the trench between metallization edges on printed circuit boards (PCBs) embedded in insulating liquid under sinusoidal high voltage sources of up to 20 kV$_{peak}$. The electric field distribution at the high field region was modelled and the electrical and optical measurements of the partial discharges obtained were correlated. PD activity around the triple region was evaluated and the rate at which pressure influenced PD events in the system is discussed.**

Keywords – Partial discharge, space charges, dielectric liquid insulation, power electronics

I. INTRODUCTION

The quest for a less expensive and more manageable pressure compensated vessel with significantly reduced weight for subsea depths of up to several thousand meters as a replacement for thick, heavy and expensive one-bar vessels for subsea power electronic converter, brings about the development of pressure tolerant power electronics for subsea operation. This could be achieved if critical components like power semiconductors, DC-link capacitors and drivers can operate with satisfactory reliability in high pressure environment. For a complete power electronic circuit to be operable in environmental pressure corresponding to subsea depths of up to several thousand meters, the circuit need to be enclosed in some uncompressible and insulating material to protect the converter components both against mechanical damage and against flashover due to electric voltage differences. The insulation material should be applicable in such a way that voids are avoided, it should serve as a heat-spreading medium, and it has to be cost-efficient due to the large volume needed. With these specifications a liquid-based insulation system is one obvious candidate [1].

The power electronic module consists of the substrate, semiconductors, and inter-connections. Application of electric field will create field stress at chip edges and the trench between metallization at the top of the ceramic substrate. For an IGBT in liquid, the highest stressed point is always at the triple point where the metal, substrate and liquid meet. Processes such as partial discharges (PDs) could be induced at high voltage such as 6.5 kV. Embedding the module in an incompressible insulating fluid relieve the mechanical stress from components and minimize processes such as partial discharges.

The three IEC test methods (60156 - for the determination of the breakdown voltage of Insulating liquids at power frequency, 60897 - for the determination of the lightning breakdown voltage of insulating liquids, and 61294 - for the determination of the partial discharge inception voltage (PDIV) of Insulating liquids) developed for transformers are not adequate for our study because of the difference in the two systems. This brings about the need for the development of test methods to study different dielectric liquids in pressure tolerant power electronic [2-4]. 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.

Ceramic substrates such as Aluminium Nitride (AlN) are often used as baseplates in high voltage power electronic modules. A report on partial discharges on AlN shows that it is electroluminescent [5]. It produces light at voltage below PDIV. This makes it unsuitable for optical partial discharge studies. PCB on the other hand is non-electroluminescent and cost effective. That makes it a good candidate as a model of IGBT baseplate for the study. A model of gaps in high voltage power electronics on PCB is suitable for the study of partial along the narrow gap between high voltage electrode and the ground potential. The aim of this work is to develop an experimental setup to study the nature of partial discharge along the trench between metallization of a PCB model embedded in insulating liquid in a pressure vessel under sinusoidal source. Although the actual voltage conditions in IGBT modules composed of dc and impulse voltage with short

This document presents results from the KPN project "Pressure Tolerant Power Electronics for Subsea Oil and Gas Exploitation - PRESSPACK " financed by Norwegian Research Council PETROMAKS program and industry partners.

This is the accepted version of a paper published in
2014 IEEE Conference on Electrical Insulation and Dielectric Phenomena - CEIDP
http://dx.doi.org/10.1109/CEIDP.2014.6995763

rise time, later studies with more realistic wave shapes will be performed. This study was performed using ac voltage and the effect of pressure on partial discharge activity is evaluated.

II. EXPREIMENTAL SETUP

A. Test Setup

A model of baseplate for HV power electronics was produced using PCB. The PCB card has dimension 38 × 24 × 1 mm^2. The board was metallized at both sides with copper sheet of thickness 420 µm. There exists a trench of 2.5 mm at the top metallization layer. The board was fixed in the pressure test cell with fixtures made from stainless steel. One of the fixtures connects the board to high voltage source and the other connects the other end of the board and the lower side to ground. The pressure vessel is filled with mineral transformer oil (Nytro 10XN) under vacuum. The pressure vessel has a piston which was used to vary the pressure from 0 bar to 100 bar.

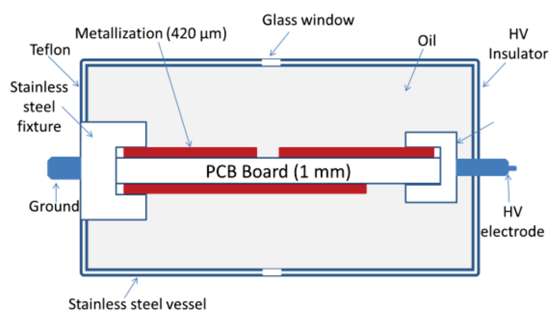

Fig. 1: Structure of the test sample

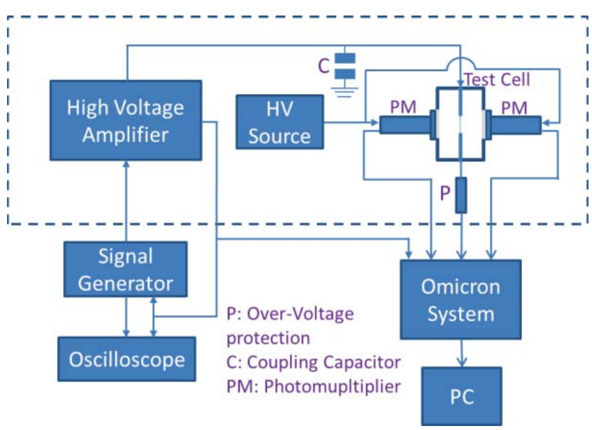

Fig. 2: Measurement Setup

B. Partial Discharge Measurement Setup

The partial discharge set-up designed to investigate the nature of partial discharge along the trench in a bespoke pressure vessel is shown in Fig 2. The measurement system consists of a TREK 20/20-HC high voltage amplifier which has maximum output of 20 kV_{peak} . The amplifier input is fed from a Wavetek 187 function generator. A coupling capacitor (1700 pF) was connected parallel to the HV source between the source and the test cell. The ground potential of the test cell was connected to the measuring impedance of the Omicron system. The Omicron system was used to record the partial discharges from the test setup. The emitted light from the discharge was recorded with photomultipliers. The calibration was done with a charge calibrator, and PD recordings were done with MPD Partial Discharge Analysis System. Two photomultipliers (PM-Philips UVP) were used to record the weak light emission from the partial discharge. The background noise for the electrical measurement is below 0.5 pC. All experiments were performed at ambient temperature.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The coupling capacitor reduces noises from the high voltage supply. It reduced the background noise from 10 pC to below 0.5 pC. The detection threshold was then set to 0.5 pC. The applied voltage was increased by steps of 1 kV with a waiting time of 1 minute at each voltage level till the inception of partial discharge. The inception voltage was considered to be the voltage where the first few PDs occur within the 1 minute. The influence of voltage variation on the number of partial discharges was examined. The partial discharge inception voltage (PDIV) at detection threshold of 0.5 pC and ambient pressure was obtained to be 12 kV_{peak}. A corresponding weak light was registered by the photomultiplier and the sound of faint discharges emanating from the test cell was monitored with oscilloscope using an acoustic emission sensor. Typical measurements obtained under 50 Hz ac are shown in Fig 3. The partial discharges were observed to be of smaller amplitudes and falls between 0.5-2.2 pC.

Application of electric field creates a high field region at the triple point as shown in Fig. 4. The electrical field generates free space charges in the liquid along the trench through electric field dependent ionic dissociation, electric field dependent molecular ionization and electrode mechanisms such as field emission and tunneling. Electrons may be injected from the sharp edges into the liquid with field emission, or withdrawn by tunneling electrons into the metal from the liquid, creating ions. These effects may increase when increasing the applied electric field. The field emission is more likely to occur due to availability of more electrons in the electrode at negative polarity than in the liquid bulk at positive polarity. When charge is injected (homocharge) in the bulk, they are transported away from the high field region. This charge will reduce the edge field during the first half cycle. In the second half of the cycle where polarity reversal occurs, the homocharges becomes heterocharges and enhances the field. The newly injected homocharges remain within the high field region counteracting the influence of the heterocharges [6]. The forces on the homocharges dominate as the field within the vicinity of the charge is higher than the field around the heterocharges. The newly created homocharges closer to the triple point are transported away, but the transport is slow since no laminar flow at the oil-board

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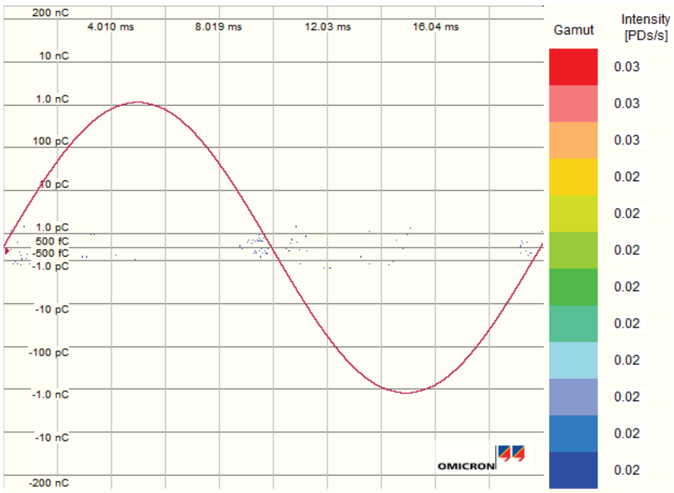
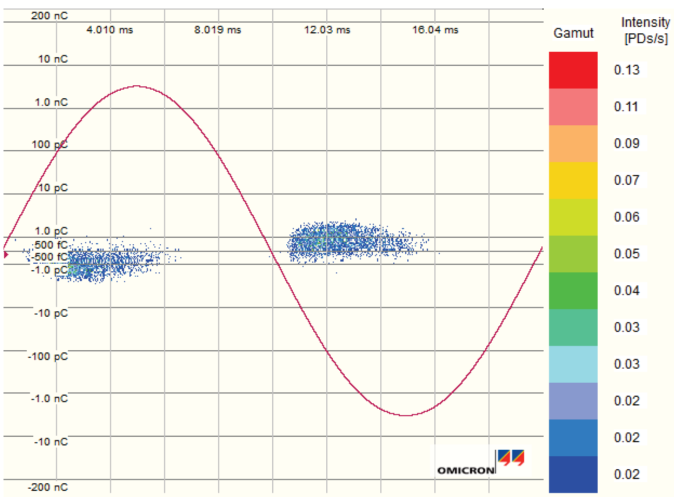
2014 IEEE Conference on Electrical Insulation and Dielectric Phenomena - CEIDP
http://dx.doi.org/10.1109/CEIDP.2014.6995763

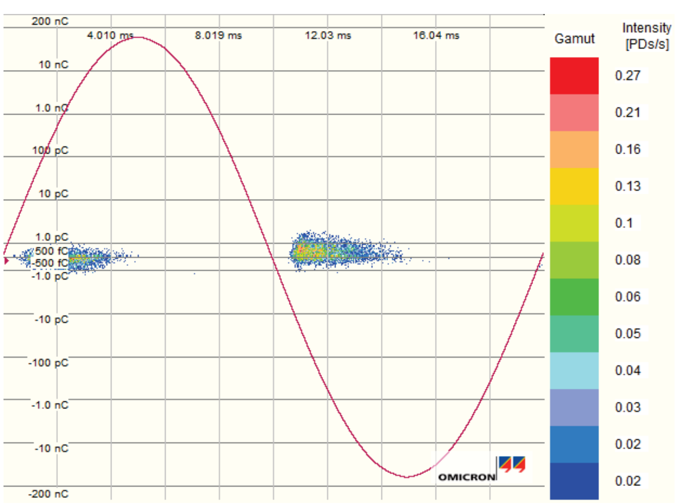
interface. This results in the space charges staying longer within the discharge surface of the solid interface.



(a) 12 kV_{peak}



(b) 13.6 kV_{peak}



(c) 18.1 kV_{peak}

Fig. 3: Distribution of PD amplitude versus phase angle.

The electric field stress may lead to local breakdown and partial discharge is initiated at inception voltage. The relative position of maximum electric field stress within the triple point region is a function of both the relative permittivity of the solid insulation and that of the insulating fluid [7]. 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 while the oil repels them. The partial discharges are most likely pulled and become surface discharges by settling along the board interface parallel to the applied field.

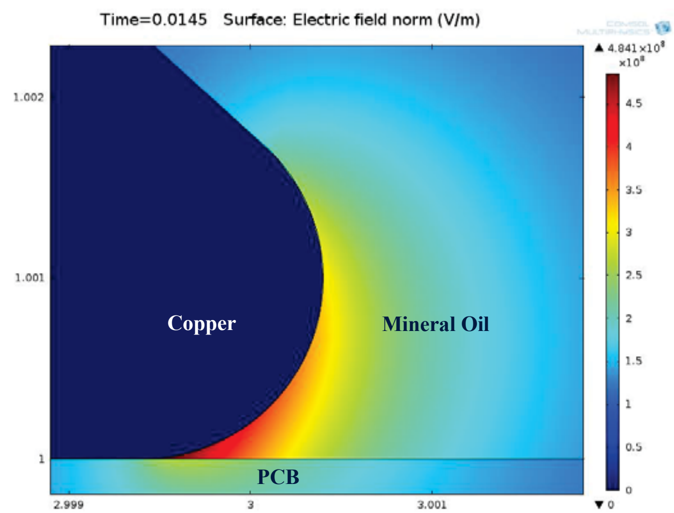


Fig. 4: Electric Field Distribution at the triple junction

The heterocharges from the previous half cycle results in an increase in the field and subsequent initiation of PD just after 0º for the first half cycle and 180º for the second half cycle as shown in Fig. 3b and 3c. This field reduces when homocharge currents start and therefore PD will cease. This is different from what was observed in point-plane gap [8]. This is most likely due to low liquid flow along the solid surface of the board. On the half cycle with negative polarity, there are more discharges close to 180º which reduced towards 270º. Increase in the applied ac voltage increased the discharge rate as shown in Fig. 5, but it did not seem to have much influence on the magnitude of the discharges.

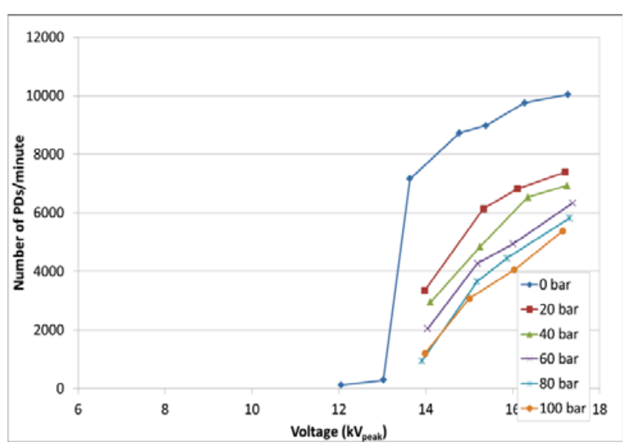


Fig. 5: Total Partial Discharge Rate versus Voltage

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More discharges were observed from negative polarity as compared with positive polarity as shown in Fig. 3. The observed polarity difference may be due to polarity specific electrode processes.

A system with solid insulation such as AlN whose relative permittivity is much higher than the oil will have higher electric field and ionization rate in the oil region. That may lead to an increase in partial discharges. The size of partial discharge may also be influenced by the relative permittivity of AlN.

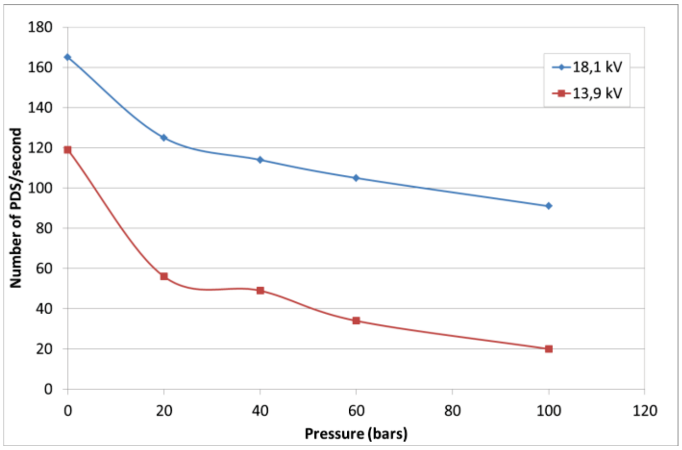

Fig. 6: Partial Discharge Rate versus Pressure

The influence of pressure on the partial discharge activity along the trench on the board was investigated. After the initiation of partial discharge within the trench of the board and above a threshold voltage of 14 kV_{peak}, significant partial discharges occur. This number of PDs increased with further increase in the applied voltage as seen in Fig. 5. Increasing the pressure of the liquid in the pressure vessel resulted in the reduction of the number of discharges as shown in Fig. 6. The PD amplitude was also observed to decrease with increase in pressure. The pressure dependence of the size and number of PDs indicates the involvement of gas phase process during the developmental stage of the partial discharge process [9]. This will limit the discharge process and streamers moving across the trench that that may cause breakdown.

IV. Conclusion

The measurements demonstrated that partial discharge activity is concentrated near zero of the half cycle because space charge effects from charges from earlier half-cycles at the oil-board interface dominates the field early in the half-cycle. The discharge settles along the board interface because of the difference in the relative permittivity of the board and oil. Later in the half cycle homocharge injection will reduce the field, so few discharges occur at the crest voltage.

Increasing the applied voltage result in an increase in PD rate but it did not have significant influence on the magnitude of the PDs.

Pressure increase resulted in reduced PD rate. The magnitude of PDs was also observed to experience slight reduction with increase in pressure.

This is as ongoing project on partial discharge activity along the trench and metallization edges of pressure tolerant power electronics. The actual voltage conditions that exist in IGBT modules composed of dc and impulse voltage with short rise time. Experiment to study the PD activity under impulse voltage and varied rise and fall times is in progress.

Acknowledgment

The contribution of Torstein Grav and Dag Linhjell of Sintef Energy Research, Trondheim, Norway on the experimental setup is acknowledged

References

[1] A. Petterteig, R. Pittini, M. Hernes, Ø. Holt, "Pressure tolerant power IGBTs for subsea applications" EPE 2009 - Barcelona.

[2] IEC 60156 ed2.0, insulating liquids - Determination of the breakdown voltage at power frequency - Test method, 1995.

[3] IEC 60897 ed1.0, Methods for the determination of the lightning breakdown voltage of insulating liquids, 1987

[4] IEC 61294 ed1.0, Insulating liquids - Determination of the partial discharge inception voltage (PDIV) - Test procedure, 1993

[5] J.-L. Augé, O. Lesaint and A.T. VU THI, "Partial Discharges in Ceramic Substrates Embedded in Liquids and Gels", IEEE Transactions on Dielectrics and Electrical Insulation Vol. 20, No. 1; 2013, pp.260-274.

[6] T. Grav and L.E. Lundgaard, "Currents in AC stressed Liquid insulated Needle Plane gap", IEEE International Conference on Dielectric Liquid, Slovenia, 2014.

[7] J. Jadidian, M. Zahn, N. Lavesson, O. Widlund, and K. BorgK. "Surface flashover breakdown mechanisms on liquid immersed dielectrics', Applied Physics Letters 100, 172903 (2012); doi: 10.1063/1.4705473.

[8] L.E. Lundgaard, O. Lesiant, Discharge in Liquids in point-plane Gap unser ac and Impulse Stress, IEEE Conference for Electrical Insulation and Dielectric Phenomenon, 1995.

[9] H.I. Marsden, P.B. McGrath, "Pressure Effects on Partial Discharges in Liquid Dielectrics" Conference Record of the 1998 IEEE International Symposium on Electrical Insulation, Arlington, Virginia, USA, June 7-10, 1998.

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2014 IEEE Conference on Electrical Insulation and Dielectric Phenomena - CEIDP
http://dx.doi.org/10.1109/CEIDP.2014.6995763