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The Correlation between Surface Tracking and Partial Discharge Characteristics on Pressboard Surface Immersed in MIDEL eN

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ABSTRACT

This paper presents the investigation of the surface tracking on pressboard surface immersed in MIDEL eN oil. In this work, the development of surface discharge was analyzed by correlating the visual records of surface tracking on impregnated pressboard and the partial discharge (PD) activities. The PD activities during the surface tracking process were analyzed in terms of Phase Resolved Partial Discharge (PRPD) patterns. Throughout the experiment, surface discharge is found as the development of tree-like patterns in the form of white marks occurring on the oil-pressboard interface. This phenomenon is generally accepted as the drying out process that involves evaporation and decomposition of the oil molecules in the pressboard pores due to the surface discharge activities on the pressboard surface layer. The development of surface discharge on the pressboard surface can continue from minutes to months or even years until failure. Thus, condition monitoring system is important to characterize this type of faulty condition. The experimental results show that there is the decreasing trend of PD magnitude during the development of white mark hallway of a gap distance which is eventually suffered from an unexpected fault.

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1. INTRODUCTION

In the past few years, manufacturers of transformer have been looking for ways to reduce the size of transformers to decrease the manufacturing cost. Fundamentally, this is realizable by increasing the dielectric strength of the transformer insulation system [1]. A well-known approach that is typically used in power transformers is by adding cellulose-based solid insulation, i.e. pressboard between phases of windings [2]. Recently, the use of appropriate nanoparticles with appropriate amount in transformer oil has also shown a positive impact on the dielectric strength of transformer oil [3].

Generally, a high voltage power transformer comprises the combination of liquid insulation and cellulose based-pressboard as major insulation in power transformer. The composite insulating system has raised an issue regarding the surface discharge at the oil-pressboard interface. The oil-pressboard interface is known as the weak point, involving electric charges deposition and boundaries which can cause the surface discharge that subsequently lead to the damage of the insulation system [4], [5]. Besides, it is also suspected that the discharge initiated at the junction between high voltage electrode and the pressboard insulation is due to the imperfection of their contact and subsequently lower the creep strength on pressboard surface [6].

Surface discharge or creepage discharge can be categorized into tracking fault which is regarded as a serious failure mode in large power transformer because it can lead to the catastrophic failure under normal operating conditions. Tracking is regarded as an electric discharges phenomenon that occur on the solid insulation leaving the conducting path which is usually observed in the form of carbonized mark and it will slowly degrade the solid material [6]. It can continue from minutes to months or even years until failure if there is no proper and effective monitoring on the transformer condition. Figure 1 shows an example of catastrophic failure along barrier board.

Figure 1. Catastrophic failure along barrier board [7]

Nowadays, the global demand for green technologies is increasing. The efforts towards the development of environmentally friendly technologies are going on elsewhere in various fields such as biodiesel [8], gas insulation [9], [10] and solid materials [11], [12]. In the case of liquid insulation, fully biodegradable vegetable oils (ester oils) have been introduced as potential alternative liquid for the replacement of mineral oil [13]. The introduction of ester oil should help to reduce the problem of non-biodegradable mineral oil spillage from ruptured and failure equipment such as transformer that may lead to the soil contamination. However, until now, the usage of ester oil is quite slow for high voltage power transformer application due to lack of understanding on the performance of this type of oil especially when combined with solid material. Therefore, it is important to seek understanding about the dielectric performance of ester oil-pressboard interface that may exist in large power transformer. This paper focuses on the study of degradation behavior of surface discharge at the impregnated pressboard immersed in natural ester oil (MIDEL eN). The surface discharge activity was observed until first appearance of full discharge and the PD characteristics were analyzed by using phase-resolved partial discharge (PRPD) pattern.

2. EXPERIMENTAL DESCRIPTIONS

2.1. Surface Discharge Experiment

The surface discharge experiment was conducted under sustained AC voltage level of 30 kV for 6 hours of experimental period. This applied voltage was determined in the range between the inception voltage and breakdown voltage. These inception and breakdown voltages were determined before the surface discharge experiment was conducted in order to select a suitable voltage level, thus, avoiding immediate breakdown during a long period of time of surface discharge experiment. For the purpose of partial discharge measurement, the measured noise level was up to 15 pC. Therefore, by considering +5 pC contingency, a 20 pC of threshold was used throughout the experimental period.

The development of surface tracking on oil-impregnated pressboard surface was correlated between visual records and the partial discharge data. The OMICRON Mtronix Partial Discharge Measurement system was used to monitor and record all the PD patterns corresponding to the surface discharge activities on pressboard surface. A digital camera with ability to capture 60 frames per second (fps) was used to record all the significant events during surface discharge experiment. Figure 2 shows the experimental setup for the surface discharge experiment.

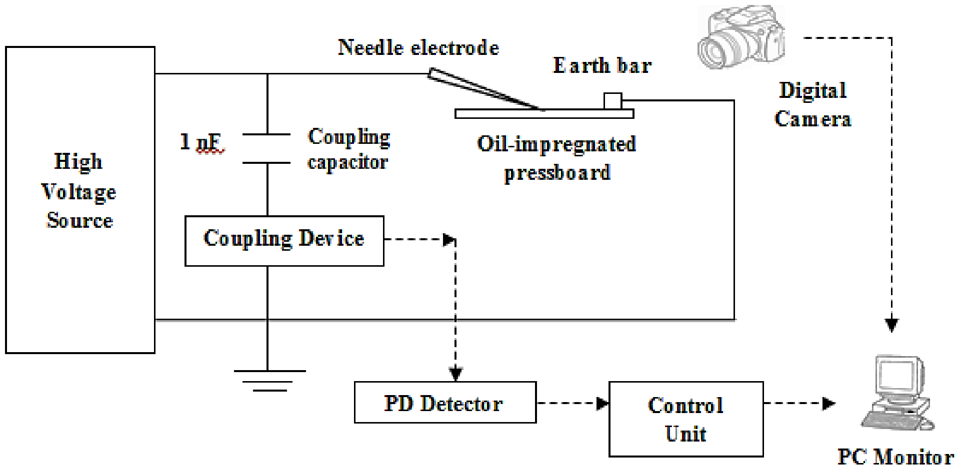
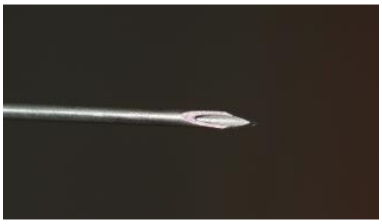


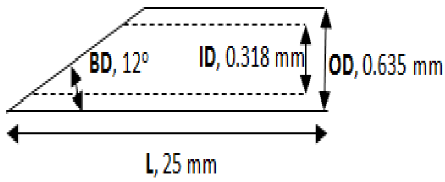
Figure 2. Experimental setup for the surface discharge experiment

2.2. Needle-Bar Electrode Configuration

Medical needle with tip radius of 20 µmwas used as a point electrode to initiate the discharge [14]. Medical needle discharge source was placed at an acute angle to the horizontal of the pressboard surface with a fixed gap distance of 30 mm from the earth electrode [15], [16]. This needle-bar electrode configuration was used to ensure that the charges built around the needle tip will distribute along the pressboard surface rather than the bulk of the pressboard [16]. Hence, this will reduce the possibility of the pressboard being punctured and subsequently can be established and sustained the surface discharge experiment for long periods of time without electrical breakdown. Figure 3(a) and (b) show the actual image and the dimension from the side edge of medical needle used in the experiment respectively. The bevel degree (BD), outer (OD) and inner (ID) diameter and length (L) of the medical needle were labeled.



(a) Actual medical needle type 23G



(b) Dimension from side edge

Figure 3. Medical needle used in the experiment

2.3. Pre-processing of Liquid Sample

Natural ester MIDEL eN oil was used as the liquid insulating for the surface discharge experiment. For the oil treatment process, MIDEL eN oil was dried for 1 hour at 70 °C and followed by a vacuum condition of 0.09 MPa for 1.5 hours at 70°C. The moisture contents of the oil sample were then measured by using Karl Fisher titration method. The moisture content of MIDEL eN oil wasbetween 150 – 180 ppm which was below than the saturation point of moisture content for ester oil, i.e. 200 ppm.

2.4. Pressboard Sample Preparation

New pressboard with a thickness of 2.15 mm, type B.3.1 from IEC 60641-3-1 which is a courtesy of Malaysian Transformer Manufacturing Sdn. Bhd. (MTM) was used in this experiment. The pressboard samples were cut into pieces of size approximately 100 mm × 100 mm. In this work, 3 % of moisture content in pressboard samples was used in the study of surface discharge characteristics of MIDEL eN oil-pressboard interface. This moisture content is expressed as the percentage by weight. In accordance with the standard of BS EN 60641-2:2004 2004 [17], the pressboard samples were firstly dried in an air circulating oven at 105 °C for 48 hours. The pressboard samples are considered dry when it is in constant mass at variation of ± 0.5 % between two successive drying. Afterwards, in order to achieve 3 % of moisture content in pressboard samples, the samples were then left in the laboratory under atmospheric condition (T = 27 to 31 ℃, RH = 60 to 70 %) until the required mass is achieved from the dried condition. The pressboard samples were then impregnated in MIDEL eN oil under vacuum condition of 0.09 MPa for 48 hours at 60 ℃[18].

3. RESULT AND DISCUSSION

This section describes the process of surface discharge behavior starting from the beginning of the experiment until the appearance of first full discharge bridges the gap distance between the needle tip and the earth electrode without resulting in a complete surface flashover or electrical breakdown. The PD data is also presented to discuss the PD pattern for each of the stage during surface discharge process.

3.1. Surface Discharge Process at MIDEL eN Oil-pressboard Interface

In the beginning of the experiment, the inttermittent arc discharge was observed instantly as the 30 kV starts to apply. The inttermittent arc discharge wasnormally observed in bluish glow discharge sparking at the tip of needle electrode. This bluish glow discharge indicates a high field region that sufficiently high enough for the ionization collisons and secondary anvalanche to take place at the needle tip [19]. This event may keep repeating up to 5 minutes at the tip of the needle electrode. The typical image of the inttermittent arc discharge is shown in

Figure *4*(a).

After a certain period of time, the white mark starts to develop across the pressboard surface and form a bush-like shape as shown in

Figure *4*(b). This stage was observed and recorded in 5 to 10 minutes after the arc discharge event. The formation of white mark indicates the drying out of liquid in the pressboard pores through evaporation and decomposition of oil molecules by the localise heating on the pressboard surface [16], [20], [21]. Consequently, the created gases by the local overheating at the pressboard surface are pushed out from the pressboard structure by the evidence of small gas bubbles floating out from the pressboard surface into the surrounding liquid. The formation of small bubbles floating out from the pressboard structure is also due to the Maxwell's stress. Based on this concept, the oil that has higher permittivity is capable to push out the lower permittivity gases from the pressboard structure [21].

Consequently, the discharge drove the extension of white mark slowly with several of branches spreading halfway across the pressboard surface as shown in

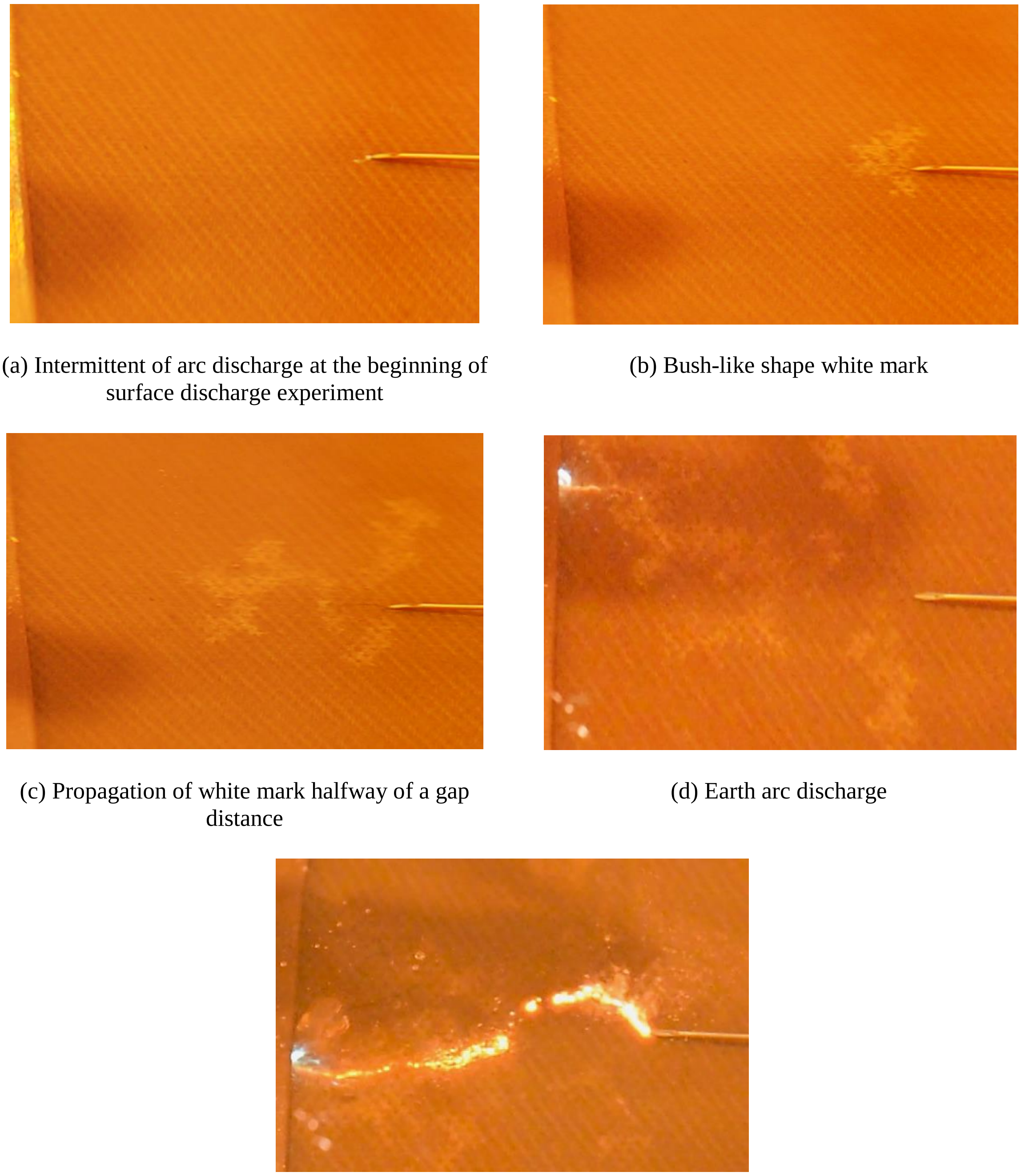
Figure *4*(c). Small gas bubbles were rose and floating out from the end of the root of white mark into the insulating liquid. The thin line of carbonized or black mark was also observed at the vicinity of the needle tip. Previous research by Zainuddin through his simulation work using finite element method (FEM) has shown that the surface discharges may cause a significant temperature increase, i.e. beyond 500 K at a very tiny region which is vicinity to the needle tip [22]. It is worthwhile noting that such a temperature level may cause carbonization of cellulose through dehydration and pyrolysis processes [23].

Next, typically after approximately 1 hour of experiment, the track of white mark starts to approach nearly to the earth bar. At this time, the repetitive bluish arcing was observed at the earth bar and bridge the track of white mark to the earth bar. The typical image of earth arcing is shown in

Figure *4*(d). Some audible crackling with the flashes was also heard during the process. To elaborate, the charge may accumulate on the pressboard surface due to the charge movement during the propagation and development of white mark on the oil-pressboard interface which is resulting on the electric field distribution [24]. The highest point of electric field at the end of the closest point of white mark is sufficient to cause earth arcing discharge [25]. The repetitive arcing at earth electrode may continue from a few seconds to minutes due to the some accumulated charges that are still undergo the ionization process at the oil-pressboard interface during the surface discharge process. Whereas some other accumulated charges have already transferred to the earth during earth arcing process.

The last process of surface discharge is full discharge event which is temporarily bridges the whole gap distance from the needle tip to the earth electrode without resulting in a complete surface flashover or electrical breakdown. The full discharge was occurred when the track of white mark is nearly touched the earth electrode and subsequently bridges the gap distance by following the white mark track on the pressboard surface. The subsequent full discharge event can re-occur by following the same white mark track or another new branch. There are two types of colors that were normally observed during this event which were in bluish and orange color. The bluish glow was occurred at the earth electrode while the orange glow was occurred on the pressboard surface following the track of white mark. This finding is similar with the previous research in [16]. Most importantly, the full discharge event is totally not the same as the surface flashover or breakdown. Full discharge is observed as a weak and partial luminous of streamer while surface flashover is observed as high illumination intensity of streamer with smoky gases [16]. An example of full discharge event is shown in

Figure *4*(e).



(a) Intermittent of arc discharge at the beginning of surface discharge experiment

(b) Bush-like shape white mark

(c) Propagation of white mark halfway of a gap distance

(d) Earth arc discharge

(e) Full discharge event

Figure 4. Surface discharge process at MIDEL eN oil-pressboard interface

3.2. Correlation between Surface Discharge Process and PRPD Pattern

Generally, for all data that have been taken, the presence of PD events at first and third quadrants of AC voltage cycle indicates the surface discharge and corona activies are taking place during surface discharge experiment. The PD patterns were also asymmetry between the positive and negative PD amplitude and phase distribution.

At the beginning of surface discharge experiment (see

Figure *4*(a)), the PRPD pattern for this stage is shown in Figure 5. Based on the PD pattern, some of the PD events were instantly developed across the instantaneous zero crossing of applied AC voltage. At this instantaneous zero crossing area, even though there is no instantaneous external high voltage stress, the electric field could still exist to develop the discharge. This is due to the presence of space charge developed as PD inception voltage is reached that helps to facilitate the discharge activity. This pattern can be observed throughout the surface discharge experiment.It should be highlighted that this PD pattern is also observed elsewherein [14].

After a certain period where the propagation of white mark in a bush-like shape (see

Figure *4* (b)), the PRPD pattern starts to change as depicted in Figure 6. Based on the PD pattern, PD activities broadly spread over the positive and negative half cycle for both first and third quadrants. There is no significant differences in the PD patterns when the white mark propagate about halfway of a gap distance

(see

Figure *4*(c)) but there is a higher intensity of PD activities that covers a bigger area in both first and third quarters (comparing Figure 6 and 7).

By comparing the results of PD pattern for the first three stages (see

Figure *4*(a-c)), surprisingly, the PD magnitudes (comparing Figure 5-7) seem decrease after beginning of the experiment until the propagation of white mark is about halfway of a gap distance between the needle tip and earth electrode

(see

Figure *4*(a-c)).The lower PD magnitude during the white mark is about halfway of a gap distance is might be due to the decreasing of constructive superposition. The decreasing of constructive superposition is caused by the differences of polarity between external electric field at the needle tip and space charge accumulation at the interface [25]. The reduction of PD magnitudes during halfway of a gap distance was also noticed in the previous research [25] which was done using mineral oil. However, the PRPD pattern recorded using mineral oil was totally different from the ester oil whereby the inception discharge of mineral oil was clearly displayed at the first quadrant of AC cycle.

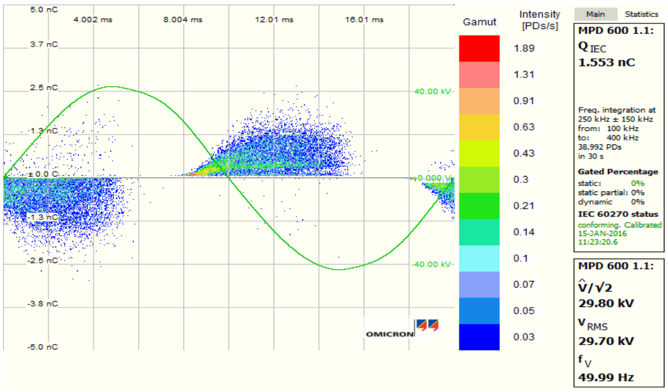


Figure 5. PRPD data for a period of 30s at the beginning of surface discharge experiment (associated with Figure 4 (a))

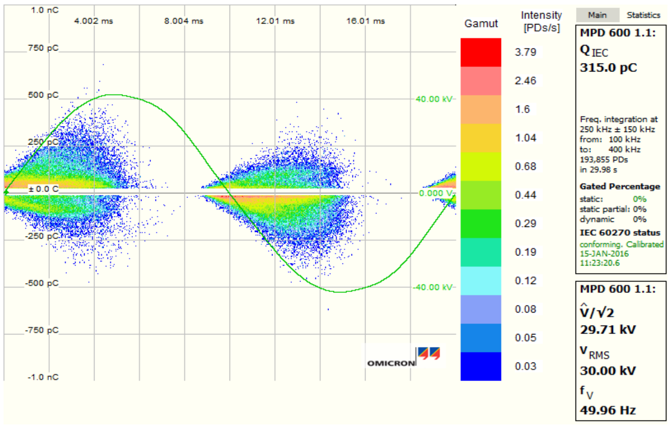


Figure 6. PRPD data for a period of 30s during the formation of white mark in bush-like shape (associated with Figure 4 (b))

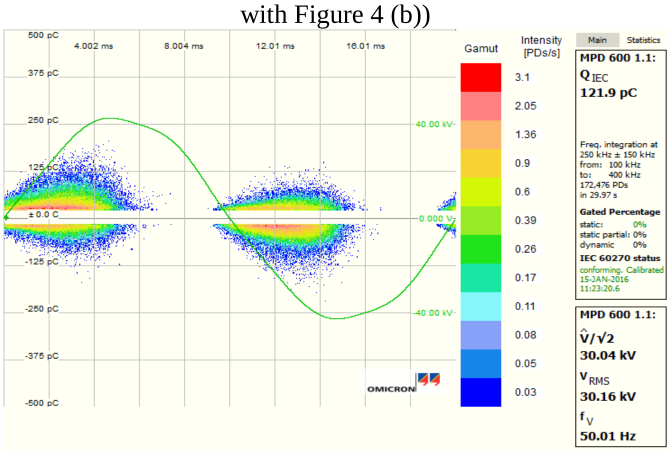


Figure 7. PRPD data for a period of 30s during the formation of white mark about halfway of a gap distance (associated with Figure 4 (c))

Next, Figure 8 shows the typical PRPD pattern obtained during the repetitive bluish arcing at earth electrode to connect the white mark and bridge the gap distance (see

Figure *4*(d)). The PRPD pattern shows that there was high PD magnitude at both peak of positive and negative half cycles suggesting corona discharge with positive and negative streamers were occurred during surface discharge experiment. However, the arc discharge was seem cluttering more at peak of positive half cycle than that the peak of negative half cycle. Therefore, it is suggested that the positive streamer give more impact on the repetitive arc discharge compared to the negative one. Besides, the high value of PD magnitude occurring at both peak of positive and negative half cycles is might be due to the high energy released during the arcing process that ionized the oil molecule. This is evidenced by the bluish arcing whereby the bluish arc enable to occur in the oil region [16]. It is also noted that there are PD activities on the first and third quadrants of AC cycle suggesting surface discharge activity is still on going.

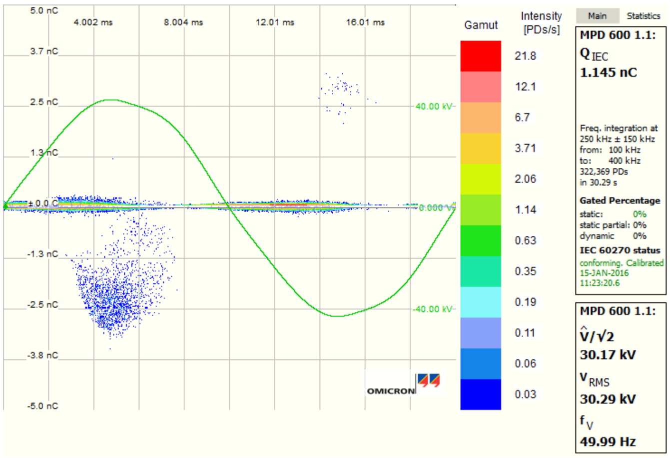


Figure 8. Earth arc discharge with high magnitude at peak of positive and negative half cycles for a period of 30s (associated with Figure 4 (d))

The repetitive of arc discharge at earth electrode can continue from seconds to minutes and consequently, the orange glow was observed bridging the electrodes following the white mark track (see

Figure *4*(e)). This event is characterized as a full discharge event which is also observed by Mitchinson and Zainuddin in their study using mineral oil [15], [16]. Figure 9 shows the PRPD pattern for full discharge event obtained from the surface discharge process. The discharges distributions are seen scattered due to the accumulation of space charges drifting toward the earth electrode. The high PD magnitude observed at both peaks of positive and negative half cycle suggesting the full discharge is a corona-like event. The density of apparent charge during this event is seen less than 3.0 nC which is less than that the earth arc discharge process (see Figure 8).

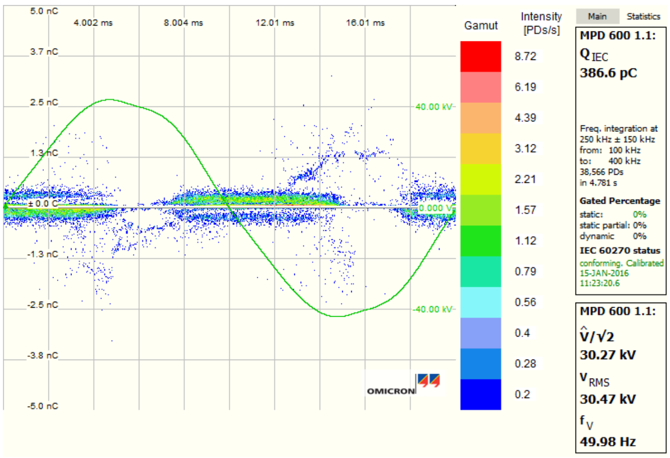


Figure 9. Typical full discharge event occurred during surface discharge process for a period of 5s (associated with Figure 4 (e))

4. CONCLUSION

A surface tracking experiment has been undertaken to investigate the degradation behavior of surface discharge on the pressboard surface immersed in MIDEL eN oil by correlating with the PD data. This work indicated that generally surface tracking on pressboard surface is characterized as a development of white mark due to the intense discharge at the interface between oil and the pressboard surface. The drying out process due to the localise heating on the pressboard structure will push out the gases in the pressboard structure to the surrounding liquid. This event can continue to develop until it bridges the whole gap distance.

By correlating with the measured data, the results turn out to be not as expected whereby decreasing in PD magnitude is observed. This decreasing trend is spotted when the propagation of white mark about halfway of a gap distance which is also observed in the previous study using mineral oil.

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