

INVESTIGATION ON THE DEGRADATION BEHAVIOR OF CREEPAGE DISCHARGE ON PRESSBOARD IMMersed IN PALM FATTY ACID ESTER (PFAE) OIL

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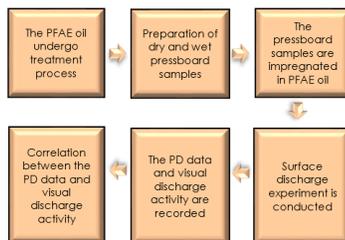
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Graphical abstract



Abstract

Creepage discharge at the oil-pressboard interface is known as the development of a conducting path which is characterized by white and carbonized marks. This phenomenon tends to cause damage on the cellulose pressboard insulation which is subsequently promote to the catastrophic failure of a transformer. One of major defects that may cause the creepage discharge to occur along the pressboard surface is an excessive moisture content in pressboard insulation. Previously, there is an extensive research concerning the effect of moisture content in pressboard on the degradation of creepage discharge at mineral oil-pressboard interface. However, none has been found on the study of the effect of moisture content in pressboard on creepage discharge using ester oil. Therefore, this paper attempts to present the investigation on the degradation behavior of creepage discharge at Palm Fatty Acid Ester (PFAE) oil-pressboard interface by using a needle-bar electrode configuration under a constant AC voltage. Dry and wet pressboard samples (moisture content of 3 %) are used in this experiment to differentiate the degradation behavior. The development of creepage discharge is analyzed by correlating the visual records of creepage discharge and phase-resolved partial discharge (PRPD) pattern. An unexpected result has been found that the number of partial discharges (PDs) for wet pressboard is lower than the dry one as the formation of white mark with bush-like pattern is observed. Eventually, as the white mark is seen about halfway of the gap distance, the PDs number for wet pressboard sample significantly dropped, i.e. by 99 % compared to the dry board which is only 38 %. Variations in the PRPD data is due to constructive and destructive superpositions of electric field. The results suggest that the destructive effect is higher on the wet pressboard compared to the dry one.

Keywords: Creepage discharge, palm fatty acid oil, oil-pressboard interface

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1.0 INTRODUCTION

Creepage discharge along the oil-pressboard interface tends to cause damage to the pressboard insulation. Pressboard insulation is mainly located between

windings in transformer as barrier. As shown in Figure 1, the main function of pressboard in a transformer is to subdivide the large oil gap into a small gap to enhance the dielectric strength of the oil gap [1-2]. Basically, pressboard insulation barrier is a thick insulation paper

made by a number of layers of laminated cellulose paper which is obtained from the softwood using Kraft process [3]. Kraft process is a process of converting soft wood logs into pulp wood by removing substances like lignin, resin and unwanted minerals from the wood [3].

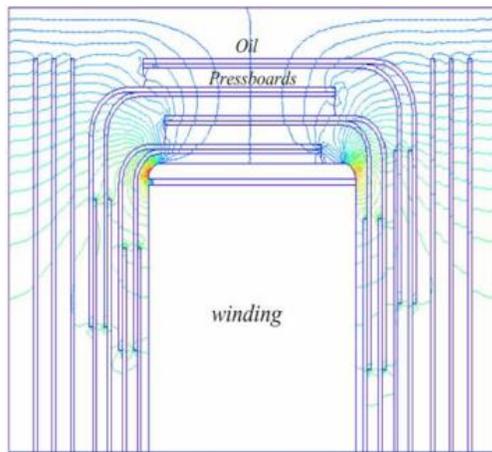


Figure 1 Structure of composite insulation system in transformer [2]

Based on previous researches [2–4], a transformer failure related to creepage discharge is associated with the development of white mark, carbonized mark and full discharge event on the pressboard surface. This failure mode leaves the irrecoverable damage on the pressboard surface which then may lead to the catastrophic failure under normal operating conditions of large power transformers. Creepage discharge which is also known as surface tracking is driven by sustained ac stress that can cause long-term damage to the pressboard surface [5]. This surface tracking can deteriorate the surface resistance until a sudden electrical discharge or breakdown if there is sufficient electrical stress [6].

The presence of water in pressboard may accelerate the propagation of creepage discharge. Arakelian and Fofana [7] state that the inhomogeneous and porous of pressboard surface that is strong polar absorbent allows the diffusion process and aid two stages of moisture adsorption. First, a strong monolayer is formed on the surface of the pressboard. Then, a polymolecular adsorption begins as the amount of adsorbate increases which is up to several tens of layers. Water has more physical properties of free water as the distance of water layers from the pressboard surface increases. As a result, this will subsequently increase the conductivity of pressboard surface. Thus, the presence of water in pressboard surface must take into account in order to avoid the damage of pressboard insulation. In addition the site measurement suggests that the excessive moisture in cellulose insulation is one of the major factors that leads to the creepage discharge failure [8].

The liquid dielectric that widely used in transformer is mineral oil and recently the use of ester oils for

distribution and traction transformers are increasing to support the green campaign which is on its good biodegradable. However, the application of ester oils as an insulating liquid for a high voltage level and large power transformer is quite slow due to the lack of understanding on its performance especially when combined with solid insulation. Importantly, the effects of moisture on solid insulation need to be considered in order to study the capability of solid insulation immersed in ester oil to withstand the long-term creepage discharge phenomenon which has not been considered in previous research. Thus, this paper addresses the creepage discharge phenomenon along the ester oil – pressboard interface. Dry and wet pressboard samples (moisture content of 3 %) are used in the experiment.

2.0 METHODOLOGY

2.1 Creepage Discharge Experiment

A constant AC voltage level of 30 kV is applied throughout the creepage discharge experiment. This applied voltage is determined from the range of partial discharge inception voltage (PDIV) and breakdown voltage. It is to ensure that there is no immediate breakdown during the experiment. This voltage level is selected by the experience of using lower voltage, i.e. 25 kV which is require a longer time for the white mark to initiate along the pressboard surface. Due to the higher level of noise during the experiment is conducted, i.e. noise free up to 15 pC, thus, a 20 pC of threshold value is set during the creepage discharge experiment by considering +5 pC contingency.

During the creepage discharge experiment, the degradation on the pressboard surface is correlated with the phase-resolved partial discharge (PRPD) pattern measured using OMICRON Mtronix Partial Discharge measurement equipment. A digital camera with ability to capture 60 frames per second (fps) is used to record all important events during which the creepage experiment is conducted. The experiment is conducted for a period of 6 hours to observe the behavior of creepage discharge at Palm Fatty Acid Ester (PFAE) oil-pressboard interface. Figure 2 shows the experimental setup to measure the Partial Discharge (PD) during creepage discharge experiment.

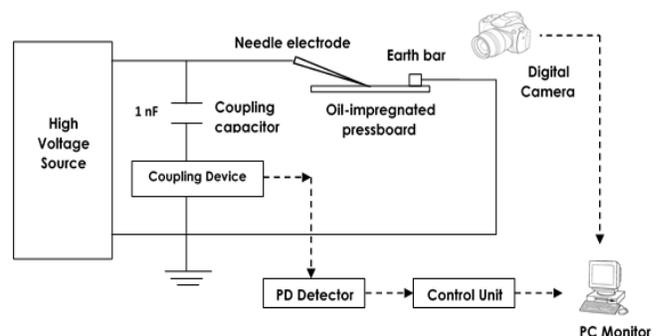


Figure 2 Experimental setup for creepage discharge experiment

2.2 Needle Bar-Electrode Configuration

Needle earth-bar electrode configuration is used in creepage discharge experiment in order to initiate the discharge along the pressboard surface [4–6]. Medical needle with tip radius of 20 μm is used as the point electrode. The gap distance between the needle tip and earth electrode is fixed to 30 mm. In this configuration, the needle is placed at an acute angle to the horizontal of the pressboard surface [4, 6, 9]. It is to ensure that the charge that built around the needle tip will distribute along the pressboard surface rather the bulk of the pressboard surface [6]. Hence, this will reduce the possibility of the pressboard being punctured compared to the point-plane electrode. In addition, the creepage discharge can also be sustained for a long period of time without electrical breakdown [6]. Figure 3(a) and (b) show the actual image and the dimension from side edge of medical needle used in this experiment. The bevel degree (BD), outer (OD) and inner (ID) diameter and length (L) of the medical needle were labeled.

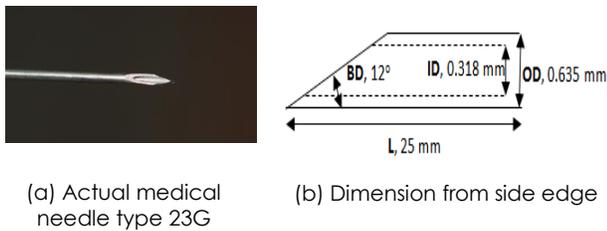


Figure 3 Medical needle used in this experiment

2.3 Sample Preparation

New pressboard of 2.15 mm thickness, type B.3.1 from IEC 60641-3-1, courtesy of Malaysian Transformer Manufacturing Sdn. Bhd. (MTM) was used in this experiment. The pressboard was cut into pieces of size approximately 100 mm \times 100 mm. In the experiment, the moisture content in pressboard samples is expressed as the percentage by weight. Two conditions of pressboard samples are used in the experiment, i.e. less than 0.5 % for dry condition and 3.0 % for wet condition. Firstly, the pressboard samples are dried in air circulating oven at 105 $^{\circ}\text{C}$ for 48 hours. The pressboard samples are considered dry when it is in constant mass at variation of ± 0.5 % between two successive drying to comply with the standard (BS EN 60641-2:2004 2004) [10]. For the wet pressboard samples, the samples are then left in the laboratory under atmospheric condition ($T = 27$ to 31 $^{\circ}\text{C}$, $\text{RH} = 60$ to 70 %) until the required mass is achieved. After these procedures, the dry and wet pressboard samples are impregnated in PFAE oil under vacuum condition of 0.09 MPa for 48 hours at 60 $^{\circ}\text{C}$ [11].

For the oil treatment process, the PFAE oil was dried for 1 hour at 70 $^{\circ}\text{C}$ and proceed with the vacuum condition of 0.09 MPa for 1.5 hours at 70 $^{\circ}\text{C}$. Afterward,

the moisture contents of the PFAE oil were measured using Karl Fisher titration method. The moisture contents were in the range (150 to 180) ppm.

3.0 RESULTS AND DISCUSSION

This section describes the flow of degradation during creepage discharge process from the early stage of surface discharge experiment until the appearance of full discharge event. The PD data are also presented to discuss the occurrence of decreasing trend in the number of discharges.

3.1 Creepage Discharge Features along PFAE Oil-Pressboard Interface

The propagation of white mark from the needle tip towards the earth bar plays an important role in the development of creepage discharge at the oil-pressboard interface until the occurrence of full discharge event. In general, Figure 4 illustrates the features of the degradation behavior in creepage discharge from the early stage until the appearance of a full discharge event at PFAE oil-pressboard interface.

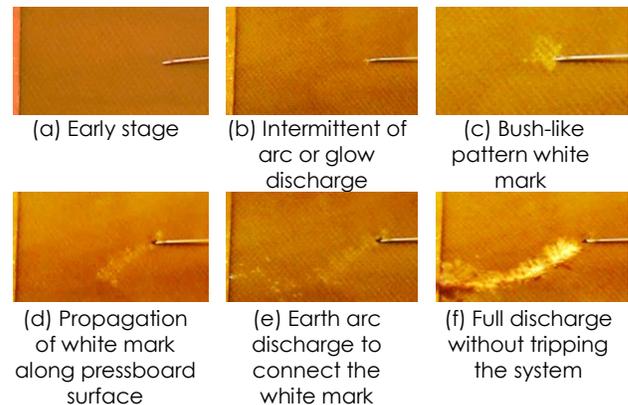


Figure 4 Features of degradation behavior in creepage discharge at PFAE oil-pressboard interface from the early stage until full discharge event

At the beginning of the experiment (Figure 4(a)), no visual indication of creepage discharge activity was observed, but PD is known to be established based on the recorded PD data. This continues for about 30 minutes for dry pressboard sample and about 5 to 10 minutes for wet pressboard sample. The result suggests that the white mark is difficult to initiate along dry pressboard sample compared to the wet pressboard. It should be noted that this observation is contradict with the previous research by Zainuddin [4] which has directly observed the intermittent of arc discharges at the beginning of the experiment with mineral oil. However, in this work, such intermittent discharges were observed in the next stage as shown in Figure 4(b). This discharge activity suggests that ionisation and

secondary anvalanche are taking place at the needle tip on the pressboard surface [12].

Generally, the formation of white and black marks, arcing event as well as full discharge event reported by Zainuddin and Mitchinson [6, 13] are also observed in this work. In this work, these behaviours are shown in Figures 4(c), 4(d), 4(e) and 4(f). Figure 4 (c) shows the bush-like white mark starts to extend slowly along the pressboard surface. The white mark indicates the drying and vaporization process along the pressboard surface by the evidence of gas bubbles [6]. Consequently, Figure 4 (d) shows the white mark extends farther with the appearance of black mark at the vicinity of needle tip and follows the track of white mark but not necessarily bridge the whole distance. A recent simulation work using finite element method (FEM) has shown that surface discharges may cause a significant temperature increase, i.e. beyond 500 K at a very tiny region that is vicinity to needle tip [14]. It is worthwhile noting that such a temperature level may cause carbonization of cellulose through dehydration and pyrolysis processes [15].

Next, when the white mark nearly reaches the earth bar, repetitive bluish arcing was observed at the earth bar to bridge the track of white mark to the earth bar as shown in Figure 4 (e). Some audible crackling was also heard during this period. This feature suggested that there is a highest electric field at the end of the white mark due to the charge accumulation which is sufficiently to cause the earth arcing discharges. The charge accumulation is due to the charge movement during the propagation of white mark along the pressboard surface which gives the conducting path for the surface currents to flow. Subsequently, the earth arcing leads the track of white mark (accumulated charges) grow toward the earth bar while the ionization process continuously occurs at the oil-pressboard interface during the creepage discharge [13].

After this process, a phenomenon of full discharge event was observed during creepage discharge phenomena as shown in Figure 4 (f). It temporarily bridges the whole gap distance from the needle tip to the earth bar without tripping the protection system. The subsequent full discharge event can re-occur by following the same track or another new branch on the pressboard surface. It is worth noting that, this full discharge event occurs frequently on wet pressboard sample, i.e. about 10 times rather than 4 times on the dry pressboard sample during the experimental period. This is might be due to the presence of excessive water which then provides excessive space charge accumulation at oil-pressboard interface.

Figure 5 shows the pressboard surface conditions after 6 hours of experimental period. The figure shows that the white mark extends more branches on wet pressboard sample compared to the dry one. Hence, it can be concluded that the discharge is more intense on wet pressboard surface compared to the dry one.

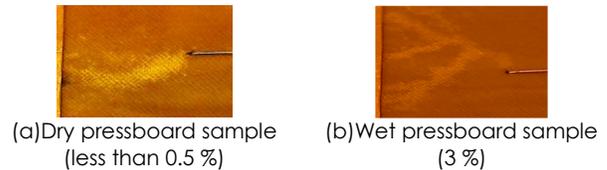


Figure 5 Pressboard surface conditions after a period of 6 hours immersed in PFAE oil

3.2 Partial Discharge Data

Figure 6 shows the PRPD pattern at the early stage of the creepage discharge experiment. The figure shows that there are PD events at the first and third quadrant of the AC voltage cycle indicating both surface discharge and corona activities are taking place during the experiment. Such results are typically obtained although no visual discharge activity as previously shown in Figure 4(a). As there is sufficient discharge activity to initiate the white mark (see Figure 4(b)), some PD start to across the zero crossing of applied AC voltage as shown in Figure 7. This pattern can be observed throughout the experimental period. At the instantaneous zero crossing, 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 that help to facilitate the discharge activity.

Throughout the experiment, as the white mark starts developing, the number of discharges was increased steadily. This is probably due to the constructive superposition of electric field [4, 13] from accumulation of charges on the white mark track. Eventually, after a certain period, the number of discharges start to decrease when the white mark has developed about halfway of a gap distance for both dry and wet pressboard samples. Similar behavior has also been observed by Zainuddin [13] in his experiment. This trend is might be due to the increase of space charge accumulation at the interface and the distribution of external electric field at the needle tip which then increases the destructive superposition in electric field. Table 1 summarizes the number of discharges for the first four stages observed during the surface discharge experiment for both dry and wet pressboard samples.

Unexpectedly, the number of discharges for wet pressboard sample is lower than dry pressboard sample starting from the propagation of bush-like pattern white mark observed on all tested samples. In addition, as the white mark is about halfway of the gap distance, the number of discharges was observed drop significantly from the third stage (formation of white mark in bush-like pattern) with 99 % for the wet pressboard samples compared to the dry one which is only 38 %. These situations are probably due to the effect of field reduction as a result of high destructive interference in the case of wet pressboard compared to the dry one.

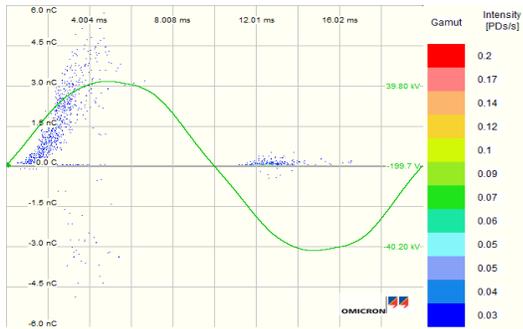


Figure 6 PRPD data for a period of 30 s at the early stage

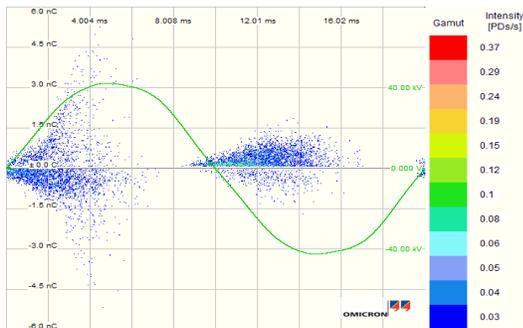


Figure 7 PRPD data for a period of 30 s as the white mark starts to initiate

Table 1 The number of discharges during the experimental period

	Dry sample	Wet sample
Early stage (Figure 4(a))	391	1218
As the white mark starts initiating (Figure 4(b))	1938	9052
Formation of white mark in bush-like pattern (Figure 4(c))	102,346	72, 957
Propagation of white mark about halfway of a gap distance (Figure 4(d))	63, 574	40

4.0 CONCLUSION

A creepage discharge experiment has been undertaken to investigate the degradation behavior due to creepage discharge at PFAE oil-pressboard interface for both dry and wet pressboard samples. The features of creepage discharge have been discussed and correlated with the PRPD data. The results suggest that the moisture content plays an important role on the initiation of the white mark and the propagation of white mark to bridge the whole gap distance. The

white mark extends faster with more branches on wet pressboard sample compared to the dry one.

For PRPD data, the constructive and destructive superpositions of electric field play important role on the trending of PD results, i.e. increasing and decreasing trends. The destructive effect is observed higher on the wet pressboard compared to the dry one.

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