Tracking and Surface Discharge at the Oil–Pressboard Interface

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A different approach to the study of surface tracking reveals a new view of the oil–pressboard interface and suggests a link between the electric double layer and the boundary layer.

Introduction

Great care is taken when designing and manufacturing large oil-filled transformers. One design requirement is to ensure that all conducting surfaces have blended geometries and are covered by solid insulation material, typically a cellulose material in the form of paper or pressboard. This prevents the emission of electronic charge that will occur from any bare conducting surfaces according to the modified Schottky process when a conductor is under high electrical stress [1]. The solid insulation effectively adds an extra barrier to charge emission. However, other phenomena can introduce charge into the insulation system under certain conditions. For example, space charge can form at an oil–pressboard interface under a high electric field due to interfacial polarization arising from the difference in permittivity between adjacent materials [2]. Partial discharges (PD) are another source of electrical charge generation. Partial discharges may occur in solid, liquid, and gaseous insulations wherever there are sharp changes or discontinuities within the insulation medium and where the electric field is sufficiently high to exceed the local breakdown value. Surface contamination is a likely site for PD due to the presence of inclusions and changes in bulk material. Finally, oil flowing across pressboard can build up static charge on the pressboard surface, a phenomenon referred to as static electrification but also known as flow or streaming electrification [3].

The movement of excessive charge over solid insulation may result in mechanical and chemical damage to material through thermal and electronic action. For solid insulators, 2 different forms of damage are generally classified. Surface damage is termed *tracking*, whereas damage through the bulk of the (solid) material is termed *treeing*. In both cases, the damage results in a permanent electrically conductive path that reduces the effective voltage withstand of the material. Tracking has traditionally been associated with solid–air interfaces and polymeric insulators [4]. However, tracking is now recognized as a significant feature at oil–cellulose interfaces and is considered a possible failure mode in large oil-filled transformers [5]. The term *creeping discharge* has been coined to describe the characteristic irreversible tree-like patterns occurring on the interface as a result of these surface discharges [6]. Surface tracking can deteriorate the surface resistance to such an extent that a sudden electrical discharge or breakdown can occur if the electrical stress is high enough. The sudden electrical breakdown is referred to as surface flashover, thus implying that the breakdown occurs in the medium above the surface [7]. Substrate material, surface finish, surface contamination, condition of fluid material, temperature, pressure of fluid, level of applied electric stress, and duration of application have been identified as the significant factors leading to surface tracking and/or flashover [8]. The oil–pressboard interface is also acknowledged as one of the main locations for interfacial polarization, as well as static electrification. Clearly, the oil–pressboard interface plays a significant role in the life of a transformer. However, many issues remain unanswered as to

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the exact nature of tracking. How can tracking in a liquid environment be reliably produced and quantified? What role does static electrification play in tracking, if at all? What defines the oil–pressboard interface?

This paper addresses some of these questions. First, the various experimental methods of producing surface tracking are reviewed, and a new approach proposed. Static electrification is also considered against a new interpretation of the oil–pressboard interface. Finally, the results of some tracking experiments on standard pressboard type Transformerboard TIV [9] are examined when using the new approach to produce surface tracking.

The Measurement and Production of Surface Tracking

The measure of the resistance of solid insulation materials to tracking in air is determined by the Comparative Tracking Index standard [10]. Two tests are available, and these use either a horizontal surface or an inclined slope. The tests employ a liquid contaminant, sprayed in droplet form onto the solid surface, to promote tracking. The standard considers only air as the fluid medium above the surface, and this raises the issue as to how to quantify surface tracking at the interface between a liquid and a solid.

For liquid–solid interfaces, several different methods have historically been used to create surface discharge. One common approach is to implement a point–plane arrangement [11], [12]. A needle is connected to a high voltage source and placed on or near the surface of the pressboard. This results in an intense space charge around the tip and causes electrical discharges to occur around the needle tip, leaving radial tracking patterns on the surface of the solid insulation. However, the needle produces a directional and intense electrical field, which can lead to a rapid electrical failure through the bulk medium when using pressboard as the dielectric. Another approach is to use a parallel plane–plane method with pressboard placed perpendicularly between 2 electrodes and with a small point source created on the surface of one of the plane electrodes and adjacent to the pressboard [13]. This method overlooks the fact that the electric field associated with the electrode arrangement is not separated from the enhanced electrical field arising from the discharge source. This makes the effects due to the localized discharge source difficult to separate from the effects of the resultant electrical field associated primarily with the electrodes.

A different method has been developed in the Tony Davies High Voltage Laboratory to overcome the difficulties of the traditional approaches [14]. This is an adaptation to the Comparative Tracking Index configuration; a needle discharge source is placed at an acute angle to the pressboard at some distance from an earthed conductor also placed on the pressboard, with the system immersed in oil. The acute angle of the needle ensures that charge arising at the needle tip is directed along the surface rather than through the bulk of the pressboard. This method has been found to reliably produce surface discharge when the voltage source ranges between PD inception and surface flashover. Three conclusions were drawn from this approach. The first is that the degree of damage due to PD is clearly time and voltage-level dependent. This means that surface tracking can be established and sustained on the oil–pressboard interface for a considerable time without electrical breakdown.

The second conclusion is that PD inception/extinction is insensitive to the gap distance from earth, suggesting that surface discharge is a localized phenomenon. Surface flashover and intrinsic oil voltage breakdown are sensitive to the gap distance, indicating that these mechanisms are associated with bulk material properties.

The third conclusion is that the presence of the solid surface depresses the intrinsic voltage withstand of the bulk oil medium so that surface flashover occurs at a lower value than the bulk medium properties would predict. The differences in the features observed between tracking and surface flashover suggest that these events occur at 2 different layers of the surface and that the structure plays a role in voltage depression from the intrinsic voltage withstand of the bulk oil.

Static Electrification

The transformer industry first became aware of the problem of static electrification in the 1970s following examination of transformer failures [3]. Static electrification is now accepted to be due to the electric double layer (EDL) at the oil–pressboard interface [15], [16]. The EDL, first proposed by Helmholtz, is the variation in potential across a surface interface between 2 different materials. It is analogous to the depletion zone in the transition region at the junction between p-n semiconductors. In the case of the solid–liquid interface, the EDL model describes a homogenous solid surface with the EDL existing in the liquid layer at a thickness of no more than 1 or 2 molecules next to it [17]. The model has been expanded to the Guoy-Chapman Stern model, which describes 2 layers: the thin Stern layer, which carries the majority of the charge, and a diffuse layer where charged liquid molecules are less densely spaced and more mobile [18].

The mechanism for static electrification is the interaction of the oil with the pressboard as the oil moves across the surface of the pressboard. The oil develops a charge depending on the surface over which it travels. If the oil travels over a region where there is an availability of free electrons (i.e., a conducting surface), then the oil acquires negative charge. Alternatively, if the oil travels across pressboard, the cellulose hydroxyl groups tend to acquire a negative charge from the moving oil, leaving the oil positively charged [17]. The oil relaxes the charge as it approaches earthed surfaces. If the relaxation does not eliminate charge quickly enough, a static electrical field can be established, which may end in a static electrical discharge [19], [20]. This phenomenon has been reported as a significant factor in some transformer failures [3], [16], [21]. Static electrification is a function of many parameters including temperature and moisture but primarily the pressboard surface structure and oil condition, specifically the oil electrical charging tendency [22]. Dry oil, dry pressboard, and surface roughness increase the likelihood of static electrification [3], [15], and it has been suggested that the presence of carboxylic groups also increases static electrification [20]. This has led to the use of oil additives to counteract it [23], [24]. Current research on static electrification focuses on the chemistry of pressboard rather than mechanical surface features such as porosity and surface roughness, which are only mentioned in passing [25].

It is clear that interfacial polarization and static electrification have the same roots through the charging tendency of different materials when in close proximity. This raises the issue of the possibility of an interaction between the electric field, which causes interfacial polarization, and the static electric field created in the EDL produced by oil flow over an insulation surface. The link is the solid–liquid interface. A closer inspection of this interface between oil and pressboard suggests that it is more complicated than first assumed.

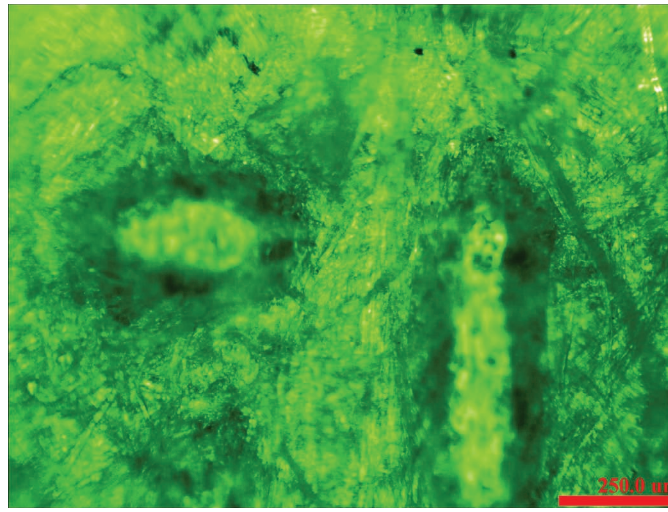

Figure 1. Morphology of dry pressboard surface at 200× magnification.

Pressboard and the Oil–Pressboard Interface

The use of the word *solid* to describe pressboard conveys the sense of a homogenous and dense material. Pressboard is in fact a light, fibrous, and porous material [26]. In use, pressboard is first dried and then impregnated with mineral oil under high vacuum conditions. This process removes moisture and gasses from the fibrous structure and refills the interstices with oil molecules. This proven method has been the key in extending the life of pressboard as an insulating material. The measure of impregnation is defined by oil absorption by mass, which is typically 13% for TIV Transformerboard [9], although it varies according to material and surface finish [27]. After the impregnation process, the oil pressboard insulation medium effectively forms a composite insulation structure with the oil.

A casual look at the oil–pressboard interface suggests that the interface changes abruptly from bulk pressboard to the bulk oil. However, a closer examination of the surface of pressboard reveals that the situation is rather more complex. Pressboard is manufactured in a range of surface finishes from a smooth (i.e., calendered) finish to a textured (i.e., cloth) finish [28]. Figure 1 shows the surface textured finish of TIV Transformerboard, which is characterized by an array of small and large dimples orthogonal to each other and set in the bulk fibrous backdrop. A microtome section reveals the edge to be quite irregular with protruding fibers and characterized by a transition region of approximately 350 μm before the bulk volume of pressboard (Figure 2). (Note: Figures 1 and 2 have been captured using a green filter to enhance features.)

The oil–pressboard interface is, therefore, not the clean edge it appears to be from a distance; in reality, there is an ill-defined interface comprising a transition region between bulk oil/pressboard composite and bulk oil. In this transition region, the ratio of oil must change from the typical value of 13% (i.e., the bulk value of oil adsorption) toward 100% as the material structure changes from the bulk oil/pressboard composite medium toward the bulk oil medium. This oil–pressboard transition zone is further complicated by the presence of the dimples and individual fibers, as shown in Figure 2. The liquid boundary layer, as defined by conventional boundary layer theory, resides just outside the "solid" surface. However, the ill-defined pressboard edge and the presence of raised fibers suggest that the extent of both the EDL and the liquid boundary layer could be greater than theory might indicate.

The classical mechanical model, with nonpolar "solid" pressboard and liquid mineral oil molecules, defines a liquid boundary layer formed by weak Van de Waals forces between the covalent molecules. The liquid molecules, closest to the "solid" medium, stick to the solid and create the so-called no-slip layer, which is equivalent to the Stern layer in the Guoy-Chapman Stern model (thus linking the Stern layer in the EDL model to the no-slip layer in the mechanical model). These molecules are fixed, and there is a gradual transition from stationary oil molecules to the oil molecules in the free stream, with the region in between forming the boundary layer (thus linking the diffuse layer in the EDL model to the boundary layer in the mechanical model). The boundary layer is small in thickness where laminar flow may occur and increases in thickness for turbulent flow. A

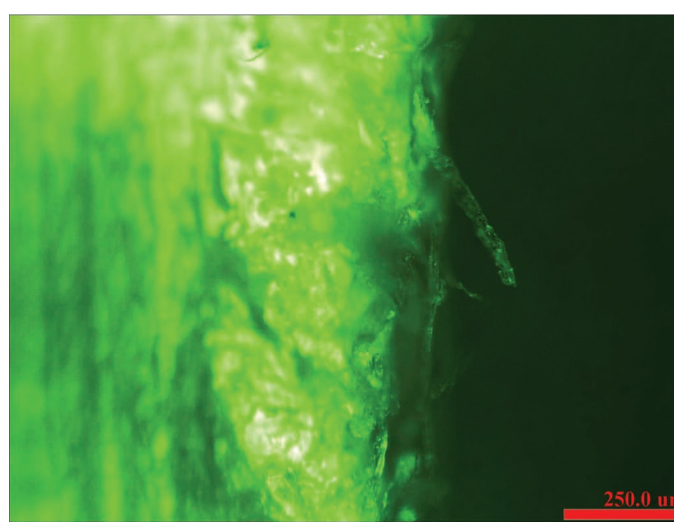

Figure 2. Microtome of pressboard edge at 200× magnification

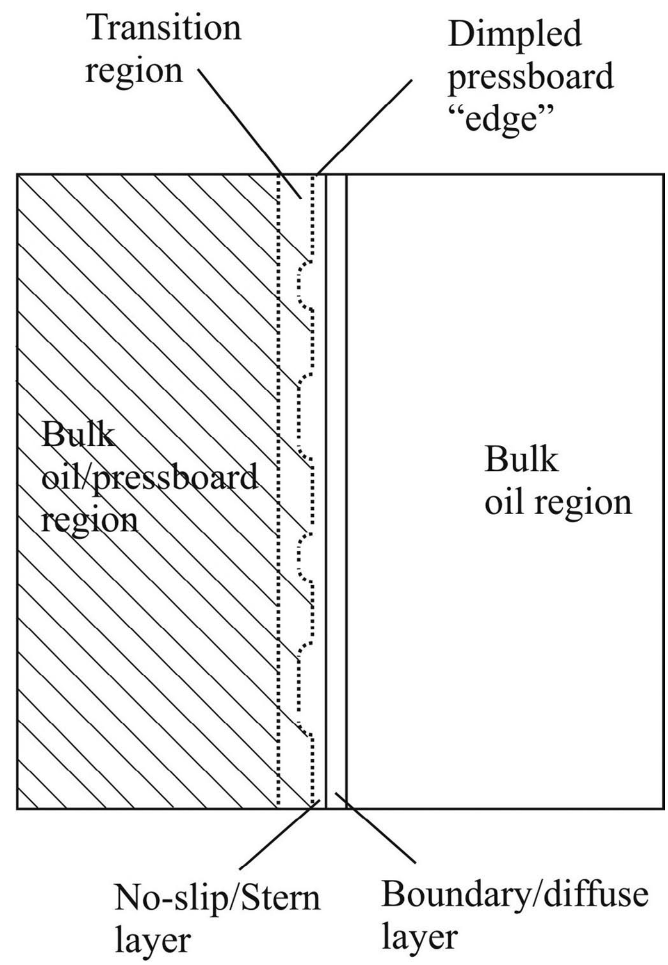

Figure 3. A new model of the oil–pressboard interface.

rough surface increases turbulent flow and the thickness of the boundary layer, whereas a smooth surface diminishes the turbulence and, hence, the thickness of the boundary layer. A new model of the oil–pressboard interface could be described as the liquid boundary (diffuse) layer (incorporating the no-slip /Stern layer), next to the transition region, which merges into the bulk oil–pressboard composite structure (Figure 3).

Features of Surface Tracking Observed Using the New Approach

A series of experiments using the new needle bar approach were undertaken on oil-impregnated pressboard conditioned to 3 to 4% moisture content, with the needle discharge source positioned 35 mm from the earth bar and with the voltage raised to between 30 kV and 40 kVrms. Partial discharge inception was reliably produced at this level, leading to sustained surface discharge with surface flashover/breakdown initiated when the voltage was raised above 40 kV. The experiments were qualitative rather than quantitative in nature; the objective was to examine surface tracking on the oil–pressboard interface. Data collection was achieved using a standard 35-mm digital camera. Partial discharge activity was monitored using the Omicron MPD600 PD system. A typical phase resolved plot of PD activity indicating surface tracking activity taken over 30 s is given in Figure 4. Some of the significant tracking and breakdown events, captured by the camera, are shown in Figures 5 to 8.

Discussion

The Figures illustrate different features in the surface tracking/breakdown process. First, moist transformer board has to be used to initiate PD. It was found to be extremely difficult to produce PD with dried pressboard (i.e., 0.5% moisture), thus indicating that the presence of the moisture is a significant factor in the tracking process. Once PD is initiated, the first promi-

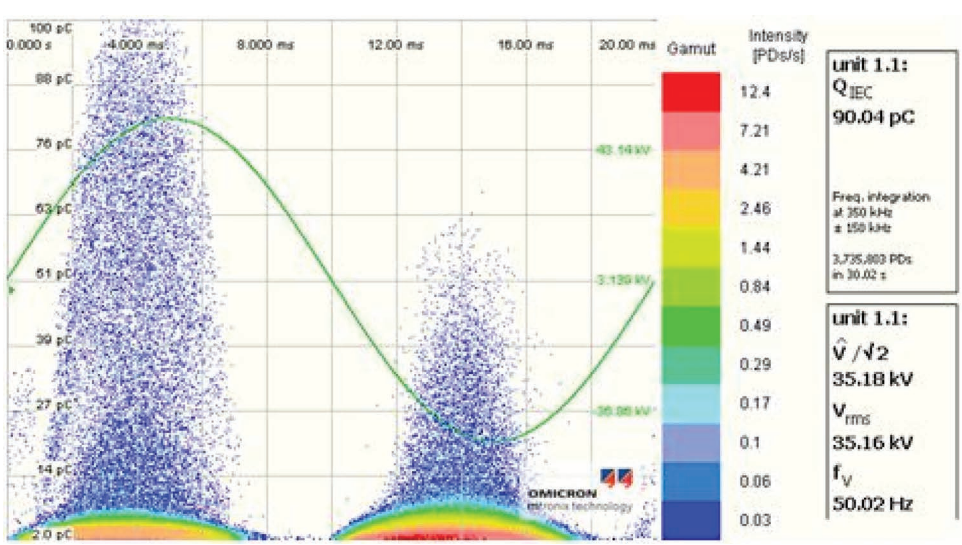

Figure 4. Phase resolved plot with needle bar at 35 kV and 35-mm gap.

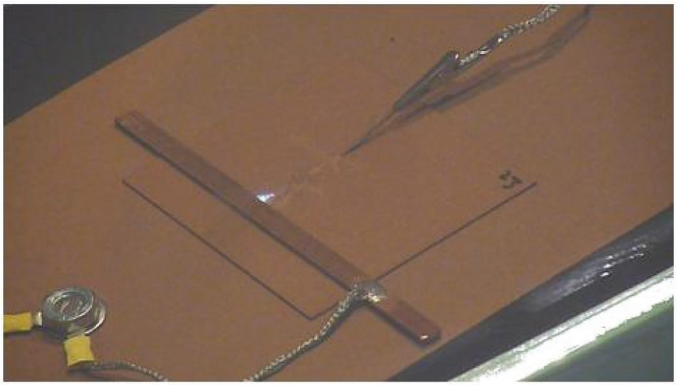

Figure 5. Initial growth of white marks and discharges in oil at the earth bar.

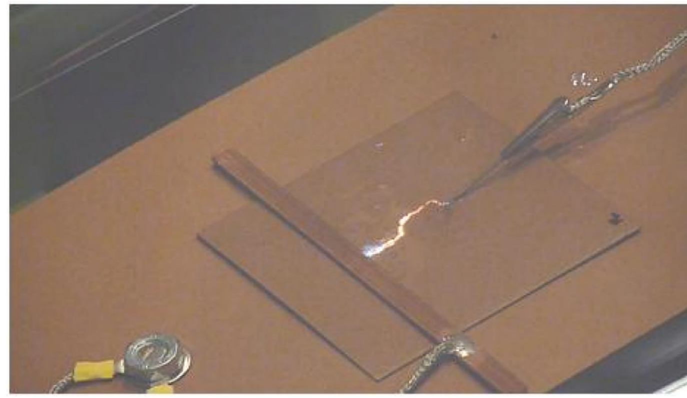

Figure 7. Full-length surface discharge without breakdown.

nent feature to be observed is the growth of white marks on the pressboard surface. The white marks grow initially from the discharge source toward the earth bar (Figure 5). These marks are indicative of a drying process as liquid in the pressboard is expelled with the injection of charge, resulting in localized reactions as evidenced by the evolution of smoke and gas. The marks develop into the characteristic fan-shaped pattern within 6 to 12 hours depending on voltage level (Figure 6). Black marks, indicating carbonization of oil/pressboard in the pressboard, follow the tracks of the white marks but do not necessarily extend the whole distance. Another feature is the random appearance of smoky particulates and gas bubbles that arise from the discharge tip. Gas bubbles may also appear anywhere along the white tracking marks as seen in Figure 6. Another feature occurs when the white marks nearly reach the earth bar. Small bluish flashes emanate from the earth bar to connect to the white marks. These flashes are clearly located in the oil above the surface of the pressboard (Figure 5). Another phenomenon is the full-length discharge that temporarily bridges the full distance from discharge tip to the earth bar without causing full electrical breakdown (Figure 7). In this case, 2 colors are clearly visible: an orange glow that occurs at the pressboard surface over the majority of the discharge length and bluish discharges at the earth bar. The most significant event is when the potential at the discharge source is increased to the system breakdown level. An instantaneous flashover occurs that is quite different from the full-length surface discharge. The breakdown discharge is more intensive and results in the evolution of significant amounts of smoky particulates and gas (Figure 8). However, the pressboard often remains largely undamaged, indicating that the discharge occurs in the oil layer. This shows that the term *surface flashover* is indeed an accurate description.

The occurrence of 2 distinct types of discharge, i.e., a slow surface tracking type with significant surface changes and a quick flashover type in the oil layer above the pressboard, suggests that 2 paths are available for electronic transport. The first path is along the transition zone/EDL/no-slip region at the oil–pressboard interface where the mingling of oil, pressboard, and other species, such as water, provides a region for space charge to accumulate and drift toward the region of lower field intensity. The second path is in the free-oil boundary layer where the increased mobility of the oil allows the propagation of a breakdown discharge at higher energy levels.

This might explain why flashover results at a lower voltage than would occur with the same oil gap separation but without pressboard as reported in the literature [14], [29]. The volume created by the transition zone/EDL at the oil pressboard, with the consequent higher permittivity than bulk oil, permits more

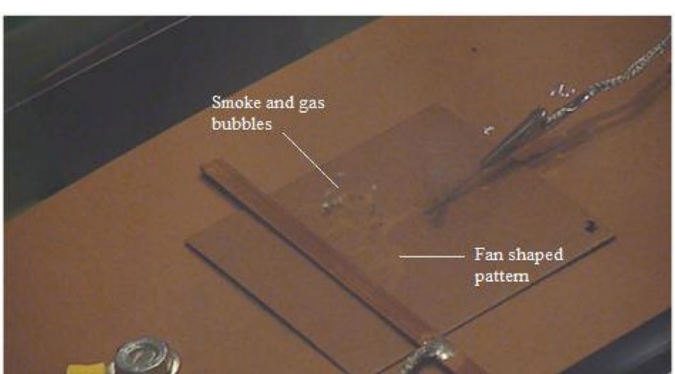

Figure 6. Growth of fan pattern from the discharge source and remote gassing.

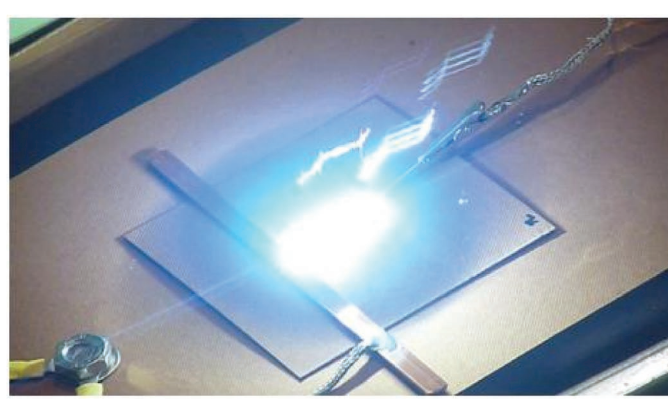

Figure 8. Flashover at 45 kV.

charge to accumulate for a given voltage than for the bulk oil medium. Space charge is thus able to progress deeper along the pressboard surface, which results in breakdown at a lower value than would be predicted with the bulk oil volume alone.

Conclusions

The oil–pressboard interface is more complex than a cursory look would suggest. The interface is better modeled as a layered structure that takes into account the EDL/oil boundary layer, and the graduated nature of the pressboard transition region into the bulk pressboard oil composite. Moisture clearly plays an important role at the interface.

The complex nature of the interface with a layered structure of oil and pressboard suggests that 2 separate paths are available for charge transport depending on the energy level of the discharge source.

One path is the EDL and oil/pressboard transition zone and is associated with lower energy surface discharges and tracking. This path allows space charge to drift under the influence of the electric field causing the degradation known as tracking. The second path is the oil boundary layer which is associated with higher energy breakdown known as surface flashover.

The observations confirm that, once tracking paths are established, significant electrical discharges can occur without breakdown. These produce gassing and particulate degradation by-products, which are common measurements used by the conditioning monitoring industry.

Interfacial polarization is associated with the mismatch of 2 media, and static electrification is associated with the liquid boundary layer and oil flowing across a solid surface. This suggests that there might be a link between interfacial polarization and static electrification. It raises the intriguing issue of the possibility of an interaction between the 2 when a system is under both high electric stress and high fluid flow rates. Further work is also required to study both the effects of fluid flow and the influence of smoothness afforded by calendered surfaces on both tracking and flashover under these conditions.

Acknowledgments

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