Electric Branch on Mineral-Oil-Impregnated Pressboard Surface Under AC Stress

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Abstract: Experimental investigations were raised to research the tracking process on mineral-oil-impregnated pressboard surface under ac voltages. This article addressed the evolution of discharge characteristics and severe stages of pressboard surface tracking by correlating partial discharge patterns from MPD600 (commercial partial discharge measurement) and images from high-speed camera. A needle-plane model was used to initiate divergent electric field and studied propagation of discharges along the solid-liquid interface. This paper compared the discharge characteristics of needle-plane model with or without pressboard under step-up sustained ac stress. It is found that the introduction of impregnated pressboard promotes partial discharges by increasing energy dissipated on or inside of the oil-pressboard interface, which is very lacking in previous references. The discharge parameters tendency and the accompanying various stages of surface tracking were investigated. A phenomenon that the stable spark discharge from needle tip extended to 30mm was called electric branch in this paper. An artificially manufactured defective pressboard was made to confirm the conjecture that the carbonized area could consume a lot of energy along the white mark. The microscopic appearance of the pressboard surface before and after the experiment was observed under SEM (Scanning Electron Microscope) and found that impregnated pressboard was severely damaged under constant ac voltage.

Keywords: ac; surface tracking; electric branch; discharge parameters; microscopic morphology

1. Introduction

Oil-pressboard composite insulation has been widely used as insulating material in ac power transformer for more than a hundred year, the typical fluid has been mineral oil, extensive tests were used to lead the insulation design practice, which is arm to satisfy the dielectric performance defined in transformer standards, there are three kinds of insulation structures in transformer including liquid insulation, solid insulation and interface between solid and liquid [1]. A simple model was made to analyze the stress distribution between two kinds of materials, which were placed in a parallel plane capacitor as shown in Figure 1.

![Figure 1. Relationship of electric stress and material permittivity diagram.](image)

In Figure 1, ε1 and ε2 represents respectively permittivity of solid and liquid material when E1 and E2 represent electric stress in each material. Their relationship is shown in Eq. (1) and Eq. (2).
\[ d_m = \left( \frac{d_1}{\varepsilon_1} \right) + \left( \frac{d_2}{\varepsilon_2} \right) \]  \hspace{1cm} (1)

\[ E_1 = \frac{U}{(\varepsilon_1 \times d_m)}, E_2 = \frac{U}{(\varepsilon_2 \times d_m)} \]  \hspace{1cm} (2)

The permittivities of mineral oil and pressboard could be observed at the Table 1, it is clear that the permittivity of pressboard is much higher than that of mineral oil, so the weaker insulation material is the liquid in this composite insulation.

| Table 1. Permittivity of solid and liquid materials [2,3] |
|---------------------------------|-----------------|
| Permittivity                    | Mineral oil     | Pressboard     |
|                                 | 2.1             | 3.9~4.9        |

Arm to set the design clearance that the dielectric stress between two materials should be distributed closer together, the oil-gaps between high-voltage winding and the tank, high-voltage winding and low-voltage winding, low-voltage winding and the core are deduced by pressboard cylinders [1], the pressboard surface insulation strength which is provided by Weidman company [4] indicates that the composite surface strength is about seventy percent of oil-gap strength. And the relationship of the uniform electric strength and oil-gap length is explained by Eq. (3), when the frequency of the supplied voltage is 60HZ, it is found that the oil-gap strength versus its length.

\[ E_o = 16.86 \times d^{-0.37} \]  \hspace{1cm} (3)

The composite surface strength is about seventy percent of oil-gap strength, therefore the strength of oil-paper composite surface is calculated as shown in Eq. (4), \( d \) presents the length of oil-paper surface in millimeter, the longer the surface length, the less the accompanying insulation strength, it is found that the interface of length \( d \) could withstand electric field up to \( E_o \). The relationship of insulation stress and surface length is plotted on a logarithmic scale as shown in Figure 2.

\[ E_o = 0.7 \times 16.68 \times d^{-0.37} = 11.80 \times d^{-0.37} \]  \hspace{1cm} (4)

![Figure 2. The relationship of insulation strength and interface length](image)

As the electric field of solid-liquid insulation is analyzed by extensive tests, it is much important to realize that the main life limiting factors of transformer is the reduction of the dielectric strength in the spaces of main insulation [5], conventional wisdom has proposed a solution by adding pressboard between oil-gap to limit the dielectric stress, which is arm to avoid local concentration of high electric field and prevent large gaps inside, the tangential electric stress along the pressboard usually controlled below 1-2kV/mm to minimize the opportunity to initiate creepage discharges [6].
There was also investigation about the development of a low permittivity pressboard obtained by blending polymethylpentene fiber with cellulose fiber [7].

Transformer insulation oil and insulation paper will be inevitably degraded because of long-term operation under sustained ac voltage, water content and partials would be increased in transformer insulating oil, especially aged ones. Local electric field concentrations may exist to initiate partial discharges, creepage discharges will occur at local high strength field area [8], especially where tip exists. Discharges will propagate along the pressboard surface layers because they cannot grow along the direction of uniform electric field from winding to winding under the barrier of pressboard cylinders [9]. It means that the electric field is divergent at the path of electric branch or carbonized mark which is formed by long-term erosion. Therefore, needle-plane electrodes model is made for laboratory research to initiate divergent electric field [10-13]. According to IEC61294, the gap distance was 50mm to approximate the electrode configuration [14], and this kind of model can cause spark discharges between needle tip and pressboard surface, over a period of time, the accumulative spark discharges can damage the pressboard surface by creating a firmly channel between needle tip and pressboard, which is characterized by "the tree-shaped white or carbonized mark", once the channels are formed, it would cause a final flashover with the passage of time [15]. In scrapped transformers, the phenomenon of electric branch or tree-shaped mark on pressboard barriers can be observed.

There were many investigations about solid-liquid composite insulation [16-21], and found that the discharge is much easier to cause damage to the solid surface in the solid-liquid composite structure. There are two types of damage could be initiated: one is driven by continuous ac voltage by long-term of energy dissipation on interface of the solid-liquid composite structure, another is driven by instant flashover by the high current arcing. Investigations about needle-plane model under lighting impulse voltage or step impulse voltage found the discharge pattern generally consist of radial ramified filamentary patterns resembling Lichtenberg Figure [22]. However, the action time of lighting impulse is about μs, makes it much harder for discharges to cause accumulative damage to the pressboard surface, ac voltage is more dangerous for an insulation structure than the impulse voltage even at a lower amplitude [23]. So only under a constant ac voltage can we find the propagation of discharges on or inside of impregnated pressboard surface layers.

Most of the work done by the previous researchers was to study partial discharge characteristic parameters of ac transformers, the partial discharge characteristic information generated in mineral or ester transformer oil under the needle-plane model [6,9] and aging assessment of Kraft paper insulation [24,25] were investigated, also including researches about properties of oil-paper insulation under all kinds of circumstances [26-29]. In particular, it is worth to research the propagation of partial discharges especial spark discharges since this kind of phenomenon is much hard, if not possible, to be observed at the transformer factory, and the white mark which is initiated by sparking discharges is much hard to find during the overhaul period of transformers since the white mark can be easy to disappear when connects with circulating air.

This paper addressed the evaluation of the discharges and various stages of surface tricking by correlating partial discharge patterns from commercial partial discharge measurement and images from high-speed camera. Proposed a new explanation according to experimental phenomena and design test to verify the new explanation, the value of partial discharges in pressboard model was also compared with oil-gap model.

2. Research Methods

2.1. AC test system

Figure 3 shows the schematic diagram of the experimental equipment. T1 was a voltage regulator with a range of 0 ~ 250V. T2 was a transformer that could output 100kV ac voltage. R was a resistor that connected the supplied voltage and test cell with a residence of 2MΩ, which also acted as a circuit protection unit especially when the breakdown occurred in simple. CK was a coupling capacitor with a value of 400 pF, R1 and R3 represented high voltage divider, Z was a
measuring impedance containing RLC circuit. In this experiment, partial discharges were measured by the commercial PD measurement named MPD600. OMICRON’s MPD600 from Austria was used as the partial discharge signal acquisition system and stored PD (partial discharge) patterns in whole period time of all tests. The input PD range of MPD600 is 0~20 MHZ. The conversion speed of the AD converter can be 64 MS/s to meet the request to measure the instantaneous PD signals during the test. The high-speed camera was the I Speed TR which could shoot at a maximum speed of 1.0×10^4 fps to ensure that the entire evaluation of surface tracking on pressboard could be captured, and images stored in 32G flash card and then transported through the Gigabit network cable to PC in real-time. The sample were needle-plane model with or without pressboard called the pressboard model and oil-gap model, respectively, which were shown in Figure 4-a and b. The whole experimental system, under the condition of no needle-plane model, had a partial discharge capacity of 5pC below 50kV and 18pC at 100kV.

2.2. Experimental Model

As shown in Figure 4-a and b, the distance between needle tip and plane electrode was 50 mm of the pressboard model and oil-gap model, each copper electrode had a diameter of 80mm and an edge randomness of 5mm.

2.3. Preparation of experimental materials

The mineral oil is 25# KARAMAY transformer oil, the oil was filtered within an oil filter equipment before the experiment. The transformer oil was transferred into a three-stage filtration cycle at 60°C for two hours to remove the moisture and impurity gases. Finally, the parameters of the filtered oil were shown in the Table 2. The needles used in the experiment were medical No. 9 needles, this type of needles could be placed against the edge of the pressboard because the needles were in the shape of a semi-aperture and could stick firmly to one side of pressboard surface. Under the optical microscope, the needle had a frontal curvature radius of 16 to 20 μm and a lateral curvature radius of 8 to 10 μm. The pressboards were the common material which were directly get
from transformer factory. A series of procedures following behind [30], the pressboards were cut into 95*80mm rectangles with 1 mm-thick to make the initial simples. Then, the samples were transferred into an air circulating oven at 105 degrees for 24 hours to remove the moisture in the pressboard. Afterwards, the dried samples were transferred in a vacuum oven of 50 Pa at 85 degrees for 48 hours to remove various gases between the cellulose fibers in the pressboards. Finally, the dried samples were impregnated with mineral oil in the same vacuum oven at 85 degrees for 48 hours. After all these, the moisture content in the impregnated pressboards were less than 0.5%.

### Table 2. The main characteristic parameters of oil before experiment.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Quality Index</th>
<th>Actual Measurement</th>
<th>Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Functional characteristics</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture content (mg/kg)</td>
<td>≮30/40</td>
<td>20</td>
<td>GB/T 7600-2014</td>
</tr>
<tr>
<td>Breakdown voltage/kV</td>
<td>≯30</td>
<td>70</td>
<td>GB/T 507-2002</td>
</tr>
<tr>
<td>Dielectric dissipation factor(90℃)</td>
<td>≯0.005</td>
<td>0.0009</td>
<td>GB/T 5654-2007</td>
</tr>
<tr>
<td><strong>Stable properties</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interfacial tension(mN/m)</td>
<td>≯40</td>
<td>45</td>
<td>GB/T 6541-1986</td>
</tr>
<tr>
<td>Acid value (mg/g)</td>
<td>≯0.01</td>
<td>0.008</td>
<td>0836-2010</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>NB/SH/T</td>
</tr>
</tbody>
</table>

### 3. Discharge characteristics and Phenomena

A continuous ac stress was supplied to the test cell during the whole period of time. Increasing 1kV every 5min until breakdown of the sample in needle-plane model occurred, which was used to simulate long-term discharge erosion to pressboard surface. It is worth mentioning that the voltage raise speed is the same for all tests at room temperature.

In all the samples used in the experiment, seventy percent of the insulating pressboards exhibit electric branch (7/10). The experimental data is obtained by integrating the average of the initial discharge voltage and the breakdown voltage of all the samples, so it could be inferred that pressboard under ac stress, the electric branch is a kind of performance that can cause the deterioration of the oil-pressboard composite insulation structure. PDIV(Partial discharge inception voltage) of pressboard model and oil-gap model was almost the same during the tests, which was consistent with [13,31]. At the same time, this paper found that the introduction of the insulation pressboard does not increase the breakdown voltage of the oil-paper insulation. An occasional breakdown occurred in oil-gap model under 54kV. At the same voltage, there was a luminous electric branch which bridged needle tip and bottom electrode. Those data were given in detail in the Table 3.

### Table 3. PDIV and breakdown voltage for experiment in pressboard and oil-gap

<table>
<thead>
<tr>
<th>Properties</th>
<th>PDIV(kV)</th>
<th>Breakdown voltage(kV)</th>
<th>Conduction Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressboard</td>
<td>35</td>
<td>55</td>
<td>Electric branch</td>
</tr>
<tr>
<td>Oil-gap</td>
<td>36</td>
<td>54</td>
<td>Breakdown(instantaneous)</td>
</tr>
</tbody>
</table>

### 3.1. Discharge characteristics

Figure 5 showed the relationship between partial discharge characteristic parameters and ac voltage. Figure 5-a displayed relationship between the average partial discharges and ac voltage while Figure 5-B, C, D represented maximum partial discharges, number of partial discharges per second and energy of partial discharges per second, respectively. All graphs were divided into five stages according to the common tendency of all data in each graph, each stage was represented by a circled number on each graph. It was clear that the average partial discharges in oil-gap was large than that in pressboard except a small part of the stage 1, 2 and 3 in Figure 5-a. The maximum amplitude of discharges in oil-gap was large than that in pressboard all the time during the test, but
if a conclusion was draw that the introduction of pressboard would weak the discharges compared with oil-gap from Figure 5-a and b, the energy of partial discharges could be ignored, only long-term of energy dissipated in pressboard caused by partial discharges can the pressboard surface be etched, that is the reason that partial discharges can cause damage to pressboard. So, the intensity of partial discharge should be measured by evaluating the energy dissipated in sample every second.

![Diagram](a)

![Diagram](b)

![Diagram](c)

![Diagram](d)

Figure 5. Diagrams of partial discharge characteristic parameters

One of the important findings is that the presence of insulating pressboard will increase the number of the partial discharges and the energy from Figure 5-c and Figure 5-d, which is consistent with the conclusion that the insulation pressboard would stimulate the partial discharge [32]. The data of the energy per second was shown in Figure 5-d, energy was calculated according to formula \( W = QU \). The energy of pressboard was larger than that of oil-gap all the time, it is obvious that the present of pressboard promotes partial discharges in pressboard. It is worth to mention that we can't prove this conclusion from average and maximum partial discharges because both characteristics of oil-gap model are generally larger than pressboard model. But the number of partial discharge and energy per second from Figure 5-c and d can strongly prove this conclusion, and this kind of characteristic parameters are hard to find in previous references.

According to the common tendency of all characteristic parameters, we could divide data of partial discharge into five stages as shown in Figure 5. At stage one, each parameter of the partial discharges basically increased with the development of supplied ac voltage, the maximum amplitude of partial discharges increased linearly with applied voltage, the energy at this stage was extraordinary small with a number around zero, but it was clear that the energy of pressboard was larger than oil-gap at stage one as shown in Figure 5-d. At stage two, each partial discharge parameters raised rapidly with voltage, and the tendency kept sloop line with an approximately 80 degrees. At stage three, all parameters of partial discharge decreased dramatically from highest to lowest. At stage four, almost all parameters kept steady with supplied voltage, an occasionally breakdown occurred at 54kV in oil-gap model, so the parameters of oil-gap were analyzed before 54kV. At stage five, there was only one line in each graph to present the property of partial discharge in pressboard model, a rapid increase of each parameter occurred, and each parameter reached a new maximum compared with that of stage two.
The propagation of surface tricking was analyzed by correlating the tendency of each partial discharge characteristic parameters and images from the high-speed camera. And it was found that each stages of test phenomena on pressboard surface were corresponding to the partial discharge parameters. From stage two to five, we could see formation, development and flashover of electric branch at the second, third, fourth and fifth stage. The experimental phenomena were shown in the Figure 6.

3.2. Experimental phenomena

3.2.1. Electric branch on pressboard surface

The development stages of the electric branch formation were shown in the Figure 6. This kind of phenomenon was called electric branch because of the unusual phenomenon about spark discharge as shown in Figure 6 a-d, a stable spark discharge with a distance developed from zero to 30mm could be observed by naked eyes, the shape was very similar to branch, so we called it electric branch in this paper.

At first stage, there was no visible trace on pressboard surface, the weak spark discharges could be caught occasionally around needle tip until 47kV.

The second stage occurred when supplied voltage was developed from 48kV to 50kV, and the spark discharges could be clearly seen at the tip of needle, as shown in Figure 6-a. The frequency of spark discharges developed from 30 to 120 times per minute. the spark discharges occurred at needle tip became intense with development of time and supplied voltage, and spark discharges from needle tip to pressboard had different direction every second, it was pretty hard to judge the spark discharges dissipated in pressboard surface layers or surrounding mineral oil because the high-speed camera was used to record surface tracking from front side.

The third stage was observed at 52 kV. As shown in Figures 6 c-e, a stable spark discharge appeared between the needle tip and the surface of pressboard due to long-term of erosion caused by partial discharges, the initial white mark was formed, after that almost all spark discharges concentrated to cause greater damage to the white mark place and promoted the extension of white mark, the initial electric branch rapidly developed toward the bottom electrode, a carbonized mark filled with spark discharges was firmed around needle tip, which could be observed by naked eyes. The spark discharge continued to develop on pressboard surface layers with a distance of 30mm from needle tip, and then the shape of electric branch changed from single to multiple. The shape of the spark discharge was very similar to electric branch, after 20 seconds from initial electric branch formation, spark discharge becomes weaker and weaker until disappear, leaving noticeable white mark on the pressboard as Figure 6-e.

The fourth stage was observed at 53 kV. As shown in Figure 6-e, the white mark extended to everywhere, but the speed of the white mark tip extension towards bottom electrode was significantly faster, both size and length of the white mark were developed with time, and small bubbles arose occasionally from tip of white mark, obviously there were also bubbles trapped between fibers of pressboard where white mark existed, spark discharges which was pretty small and weak could be observed occasionally at the tip of the white mark, the extension speed of white mark became faster when the white mark tip had a distance of 8mm to bottom electrode, a stable weak spark discharge existed at the tip of white mark and lead the extension of white mark to the direction towards bottom electrode.

The fifth stage is observed at 54 kV of supplied ac voltage. As shown in Figure 6-f and g, at first a small spark discharge bridged tip of white mark and bottom electrode, but the energy was not large enough to cause flashover at that time, after 5 seconds the first flashover occurred with a spark discharge connected needle tip and bottom electrode, a luminous flashover occurred on the surface of pressboard, the most luminous place was around needle tip where the electric stress was also the highest, after that a cloud of gas raised from bottom of white mark which was considered to be created by the evaporation and decomposition of the mineral oil and moisture in pressboard as shown in Figure 6-h.
Once the channel between needle tip and bottom electrode formed, flashover was much easier to be initiated along the path of the white mark. Since the energy of the first flashover was not large enough to tip off supplied voltage, a second flashover occurred at the same place of the white mark channel at 54kV for 3min as shown in Figure 6-i, then the breakdown of white mark channel occurred suddenly with larger noise and stronger glow than the first flashover as shown in Figure 6-j. At the end of the experiment, a black carbonized mark was observed beneath needle tip as shown in Figure 6-k.

The impregnated pressboard was transferred into a vacuum oven for further test, the stress of vacuum oven was controlled under 5mbar, there were many tiny bubbles raised up from white area on pressboard surface layers and then the corresponding white area was disappearing. The detail information was given in discussion section in this paper.

![Figure 6. Various stages of formation and development of electric branch on pressboard surface](image)

### 3.2.2. Breakdown moment in oil-gap model
There were no much test phenomena except the breakdown moment in oil-gap model compared with the pressboard model. The phenomenon of breakdown moment was captured by the high speed camera at $1.0 \times 10^4 \text{fps}$ as shown in Figure 7, we recorded images from the lateral side of oil-gap model. At first a short spark discharge occurred at bottom electrode, and an electric spot existed at needle tip, then there was an electrical connection channel from needle tip to bottom electrode, finally an intense glow occurred in oil-gap model with strong noise, the maximum partial discharge raised to 14.6nC caught by the partial discharge measurement MPD600 before breakdown moment.

A tiny spark discharge from bottom electrode firstly formed, then a clearly spark discharge bridged needle tip to electrode bottom with a sloop angle about 30 degrees as shown in Figure 7-a and b, this kind of phenomenon was influenced by two reasons: one was the smoothness of electrode bottom. Since the surface of electrode was hard to make into complete smooth, there was always some small tips. The second reason was that the needle tip is not a real smooth half taper shaped at the end side, so it might initiate discharge with an angle. It was tested four times under the same condition, the angles of the final breakdown were same all the time, but it was not found the same phenomenon as shown in Figure 7-a since the instant discharge was greatly hard to catch.

![Figure 7. Breakdown moment of the oil-gap model](image)

3.3. PD patterns

The evolution of partial discharges was measured by analyzing PD patterns shown in Figure 8. During entire test, a commercial partial discharge measurement was used to record PD patterns, six cops of PD patterns in pressboard and oil-gap were provided for comparisons as shown in Figure 8.
The evaluation of partial discharge was analyzed by collecting partial discharge for one minute especially occurred at the end of five minutes every step. As shown in Figure 8, the deeper color corresponded more discharges at each graph. The partial discharge characteristic parameter tendency was divided into five stages, it was found that the corresponding partial discharge patterns could also be divided into five stages according to overall PD patterns. The graphs on the left represented partial discharges in oil-gap while the right represented partial discharges in pressboard.

At stage one, overall partial discharges in pressboard model and oil-gap model were not differ, but the PD in negative half was promoted by the introduction of impregnated pressboard compared...
with oil-gap while the PD in positive half circle is not differed as shown in Figure 8-a and b. At stage two, both amplitude and pattern of PD patterns were much different from stage one, the maximum positive PD could be as large as 4nC, there is severe zero-crossing phase PD in this pattern as shown in Figure 8-d. The accompanying PDs could be 4.5nC at the end of stage two, at that moment the amplitude of discharges around zero crossing instants could reach to 900pC as shown in Figure 8-f. At stage three, both amplitude and pattern of PD were decreased dramatically from 4.5nC to 2nC as shown in Figure 8-g and h. At stage four, the PD kept steady to around 400pC as shown in 8-j. At stage five, the PD increased rapidly from 400pC in stage four to 8nC as shown in Figure 8-l, at this stage, there were more discharges occurred around zero-crossing area compared with the end of stage two, since the breakdown is not a kind of discharge, MPD600 stopped to record before the moment of final flashover.

3.4. Microscopic appearance

A small piece was cut off from mineral-oil-impregnated pressboard simple to contrast difference of pressboard surface before and after test, the SEM (Scanning Electron Microscope) was used to observe and analyze destruction effect on fibers in pressboard under ac stress, it could be clearly observed the integrity and continuity of cellulose fibers in the intact pressboard from Figure 9-a and b, the surface of the pressboard was smooth at 100x magnification as shown in Figure 9-a. Four continuous fibers could be easily observed under 1000x magnification as shown in Figure 9-b.

There were many fibers breakages existed in pressboard after test compared with the pressboard surface before the experiment as shown in Figure 9-c, and the integrity of the pressboard surface layers were destroyed totally, two broken fibers could be clearly seen on the surface of impregnated pressboard surface under 1000x magnification as shown in Figure 9-d. It was found that the pressboard surface was widely distributed compared with the pressboard before the experiment under the observation of the SEM.

![Figure 9. Microscopic morphology of pressboard surface under AC stress](image)
4. Discussion

The evolution of surface tricking in five stages could be investigated by correlating PD patterns from the MPD600 and images from the high-speed camera, it is found that the partial discharges are much easier to cause damage to solid insulation [33]. In stage one, we could see a stable rise of both average and maximum partial discharge from PD patterns, in other words, the energy dissipation in pressboard increased with supplied ac voltage, the accumulative energy dissipated around needle tip could cause damage to impregnated pressboard. In stage two, there were spark discharges from needle tip extending to pressboard or surrounding mineral oil, which could be observed by naked eyes, with a period of time, the frequency of spark discharges increased from 30 times per minute to 120 times per minute, the accompanying PDs raised rapidly to an amplitude as large as 4.5nC, and there were also extensive discharges occurred around or even before the zero-crossing instants, the best explanations for this kind of phenomenon would be the memory effect of solid surface for hetero space charges [34,35] and residual low density channels [36,37] left by subsequent discharges under sustained ac stress. There was no trace on the surface of pressboard at this stage. In stage three, a continuous spark discharge occurred between needle tip and pressboard with a distance developed from zero to 30mm, the spark discharge continued to extend to a distance of 30mm from needle tip with a shape of branch under the energy dissipated in white mark, some small bubbles emerged from white area, a part of bubbles attached to the pressboard and became larger. After that the stress of spark discharge became weak until disappear, the PD decreased dramatically at this stage. In stage four, there was no spark discharges could be seen on pressboard surface, but a small spark could be observed at needle tip, the white area became large both in size and length, the tips of white mark tended to expand at different direction, but the speed of the white mark tip extension toward the bottom electrode was faster, there are more bubbles arising from the path of white mark compared with stage three, the maximum of PD kept steady to 400pC at this stage. In stage five, a tiny spark discharge bridged the white mark and bottom electrode instantly and then disappear, then a luminous spark from needle tip to bottom could be seen, afterwards, a flashover occurred, since the energy of first flashover is not enough to tip off the supplied power, a second flashover burnt the fibers in pressboard surface layers and left irrecoverable carbonized mark around needle tip, PD measure recorded PD patterns before the final breakdown since the final one is not partial discharge anymore. The amplitude and overall pattern was rise rapidly from 400pC to approximately 10nC before breakdown moment in stage five.

After the test, the pressboard simple was transformed to a vacuum oven for further investigation, the stress of vacuum over was below 5 mbar. A lot of small gaseous bubbles raised from the white area, the white mark generally disappeared, there was only a carbonized mark around the needle tip remained in the end.

This kind of phenomenon proves the white mark is formed by gaseous bubbles which was considered to be created by the evaporation and decomposition of mineral oil and moisture [8], this reason could explain why there were small bubbles raised from tip of white area when the white mark extended to the bottom electrode at stage four, due to the low density of the residual channels and gaseous bubbles nature, the propagation of subsequent discharges could be promoted [36,38].

Another phenomenon that the carbonized area remained around needle tip was also significative for understanding the evolution of surface tracking on impregnated pressboard. When the second flashover occurred at test, the supplied power was not tipped off instantaneously, it means the voltage in pressboard model raised to the level of same magnitude compared with the voltage before breakdown, since the channel between needle tip and bottom electrode was already formed by the first breakdown, it should be easier for another breakdown to occur at the same path to initiate a more luminous flashover. But this could not find during the test, it was found that there was no much flashover occurred after the second flashover even under the same ac voltage within around 10 seconds, after that a flashover occurred occasionally along the same path of the first and second flashover.

Due to this kind of phenomenon, a conjecture was proposed that the carbonized mark around needle tip on pressboard could dramatically consumed the energy of discharge, in order to prove
this conjecture, a small carbonized mark was made at the path of white mark, when the spark discharges initiated a white mark with a distance of 15mm, cut off supplied power and then got the impregnated pressboard out of the model, then an electric iron was used to carbonize the middle of the white mark on pressboard surface layers. Afterwards, the new simple was transferred into an air circulating oven for 24 hours to impregnate simple firmly. After these procedures, the impregnated pressboard with the carbonized area artificially manufactured at the path of the white mark was put back to model for test, and the breakdown voltage of the new simple dramatically reached to 79kV. The breakdown moment of simple was captured by high speed camera as shown in Figure 10.

![Figure 10. Breakdown moment of pressboard with artificially manufactured carbonized area](image)

At first, there was a stable electric spark from needle tip to the carbonized area at 42kV, at which level the spark discharge was hard to initiate on an intact pressboard. Then the spark discharges became brighter with the development of voltage between 42 to 59kV, the carbonized area on the pressboard became larger both in size and length. Afterwards, the spark discharges became weak at the voltage between 60 to 78kV. Finally, the instant breakdown occurred at the time of 4min under 79kV.

The entire progress of breakdown was recorded by the high-speed camera as shown in Figure10. The white mark on pressboard surface extended to bottom electrode with high speed, an electric spark bridged needle tip and bottom electrode as shown in Figure 10-a, which could be observed by naked eyes. Then a luminous flashover occurred at the same path of white mark, the high current arcing caused the evaporation and decomposition of mineral oil and moisture, a large fire was initiated at the path of the white mark. After test, a carbonized path with a distance about 15mm from the needle tip place could be observed as shown in Figure 10-h, the carbonized area artificially manufactured was in center of carbonized mark path. The needle tip was melted under high temperatures at breakdown moment compared with that before test under an optical microscope as shown in Figure 11-a and b.
The breakdown voltage of the carbonized area artificially manufactured simple was improved significantly to 79kV compared with 55kV of intact pressboard. A conclusion could be initiated by analyzing images caught by high-speed camera, with the introduction of the carbonized area artificially manufactured in white mark on pressboard surface layers, the energy of partial discharge was consumed dramatically due to the carbonized area was in the path of white area.

![Figure 11. Shape of needle tip before and after text](image)

5. Conclusion

The evaluation of partial discharges and various stages of surface tracking were investigated by correlating images from high-speed camera and PD patterns from MPD600, the tendency of partial discharge characteristic parameters was divided into five stages, the energy of partial discharges in pressboard were larger than oil-gap under ac voltage in all five stages, it is found that pressboard stimulated partial discharges in needle-plane model by increasing energy dissipation on or inside of pressboard layers.

The formation, development and flashover of electric branch occurred on impregnated pressboard surface layers at the second, third, fourth and fifth stage were also investigated by correlating images from high-speed camera and MPD600, the accompanying overall PD patterns also raised or decreased dramatically at various stages from almost 10nC to 400pC. It was found that the white mark was initiated by long-term erosion, especially the energy dissipated on or inside of impregnated pressboard surface layers by spark discharges which was firstly observed at 48kV, and then the white mark extended into tree-shaped mark drove by spark discharges even at a distance of 30mm from needle tip, at last the white mark path and the bottom plane was bridged by a tiny spark discharge, there were always severe flashover occurred since the energy was not enough to tip off supplied voltage, usually the most luminous flashover was the final flashover.

The breakdown moment of oil-gap was also analyzed according to images recorded by the high-speed camera, the reason why the breakdown channel had a sloop angle from vertical direction could be that the needle tip is not a real smooth half taper shaped at the end side. The breakdown voltage of new sample which had an artificially manufactured carbonized area on the path of the white mark was dramatically up to 79kV, it proved that the carbonized area could consume extensive energy dissipation in the pressboard. The cellulose fibers were severely damaged under sustained ac voltage under the Scanning Electron Microscopy.

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